Climate of Minnesota

Part XVI

Incoming and Reflected Solar Radiation at St. Paul

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Station Bulletin 580-1987 (Item No. AD-SB-3276)
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Authors:

Donald G. Baker is a professor in the Department of Soil Science, University of Minnesota;
David L. Ruschy is a technician in the Department of Soil Science, University of Minnesota;
Richard H. Skaggs is a professor in the Department of Geography, University of Minnesota.

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INCOMING AND REFLECTED SOLAR RADIATION AT ST. PAUL, 1963-1985

Donald G. Baker, David L. Ruschy, and
Richard H. Skaggs

INTRODUCTION

Solar radiation is the driving force for weather systems that constantly form, dissipate, and reform as they circle the globe. The same can be said for the relationship of the hydrologic cycle to solar radiation. A portion of the solar beam is collected in green matter as an integral element in photosynthesis, and, in a different form, solar energy has been stored in the coal, oil, and gas reserves of the earth. In effect, solar radiation is the essential element for all natural processes taking place on the earth. Today, the direct capture of solar radiation for heat and energy is part of a technology developing to replace or supplement the more standard energy sources of coal, oil, and gas.

The objective of this study is to provide solar radiation information that is both broader and more detailed than provided in the preceding publications dealing with solar radiation in Minnesota (Baker, 1971; Baker and Klink, 1975; and Baker, 1977).

INSTRUMENTATION AND SITE DESCRIPTION

The instrumentation used in this study is part of the microclimate research station on the St. Paul campus of the University of Minnesota. The station is located at 44°59'N, 93°11'W, and is 971 ft (296 m) mean sea level. The site provides an essentially unobstructed view of the sky hemisphere.

The site is located within an area devoted to small agricultural test plots. The general area is best described as a modified rural environment, since there has been a gradual encroachment of private residences and university buildings. The central business districts of St. Paul and Minneapolis are approximately 5.2 mi (8.3 km) southeast and 4.2 mi (6.7 km) west-southwest, respectively, of the microclimate station.

Solar radiometers used in this study are of two types. One, a pyranometer, has the sensor under a dome of special glass that responds to wavelengths between about 0.35-2.0 μm. The radiometers used were 50 junction pyranometers with sensitivities of about 7-8 millivolts per 1 cal/(cm^2 min) or 697.6 W/m^2. (The original measurements were all made in cal/cm^2 and have been converted to MJ/(m^2 day) or W/m^2 for this study.) Radiometer output was recorded on circular chart single-pen recorders with a built-in mechanical integrator. Calibration is traceable to secondary standards maintained by the manufacturer.

The pyranometer is most commonly used to measure total incoming solar radiation which includes both the direct beam and diffuse radiation components. Pyranometers are usually oriented horizontally so that the shortwave (solar) radiation from the sun and the sky hemisphere above the instrument is received on the sensor just as on any exposed horizontal surface.

In addition to the pyranometer measuring the incoming direct beam and diffuse solar radiation, a second horizontally oriented pyranometer measured only the diffuse solar radiation. This was accomplished with a moveable metal shadow band, termed an occultation ring, mounted to keep the pyranometer sensor always shaded from the direct beam of the sun. No attempt was made to correct for the portion of the sky obscured by the occultation ring. For days of average cloudiness, the suggested increase in measured diffuse radiation ranges between 3% more than indicated in November, to 17% more from April through June. The metal band acting as the ring is 3 in (7.6 cm) wide.

On occasion, pyranometers may be oriented other than horizontally. At the St. Paul microclimate station other pyranometers have had the following orientations: a) inverted to measure reflected solar radiation; b) 90° from horizontal and facing south, to duplicate solar radiation reception on a south facing vertical surface; and c) 55° from horizontal and facing south, to duplicate a position commonly used at these latitudes for stationary solar collectors. As a compromise between summer and winter solar altitude positions, an accepted "rule of thumb" orientation for a stationary solar collector is that it faces south at an angle from the horizontal equal to the local latitude plus 10°. Since St. Paul is at about 45°N, the compromise position for a collector is to be tipped 55° from horizontal and facing south.

The pyranometer used to measure reflected radiation was mounted 4.9 ft (1.5 m) above the surface on an arm extending 6 ft (1.8 m) southward from the vertical support. Approximately 90% of the reflected radiation below the pyranometer came from an area with a radius of about 14.4 ft (4.4 m) (Reifsnyder and Lull, 1965).

The second kind of instrument used was the pyrheliometer which measures only the direct solar beam. This instrument has a special mounting that keeps it always pointed at the sun such that the sensor surface is kept perpendicular to the solar rays. A very small aperture on this instrument, in combination with its long tube-like construction with internal baffles, prevents diffuse radiation from entering and impinging upon the sensor.

The units of solar radiation used in this bulletin are Watts/meter^2 (W/m^2) for instantaneous values, and mega Joules/(meter^2 day)[MJ/(m^2 day)] for daily values. As already noted, the original measurements were made in calories per square centimeter (cal/cm^2). With respect to other comparable energy units (List, 1958):

$$1\ \text{MJ} = 1 \times 10^6\ \text{Joules}$$
$$1\ \text{MJ/m}^2 = 23.89\ \text{cal/cm}^2$$
$$1\ \text{MJ/(m}^2\ \text{min)} = 23.89\ \text{cal/(cm}^2\ \text{min)}$$
$$1\ \text{MJ/(m}^2\ \text{min)} = 1.67 \times 10^4\ \text{W/m}^2$$
$$1\ \text{MJ/(m}^2\ \text{day)} = 23.89\ \text{cal/(cm}^2\ \text{day)}$$
$$1\ \text{MJ/(m}^2\ \text{day)} = 88.05\ \text{BTU/(ft}^2\ \text{day)}$$

$$1\ \text{W/m}^2 = 1.433 \times 10\text{-}3\ \text{cal/(cm}^2\ \text{min)}$$
$$1\ \text{W/m}^2 = 59.88 \times 10\text{-}6\ \text{MJ/(m}^2\ \text{min)}$$
$$1\ \text{W/m}^2 = 52.83\ \text{BTU/(ft}^2\ \text{min)}$$

DATA RECORD

The basic time units used in this study are the calendar month and the climatological week. For the latter, week 1 is March 1-7 and week 52 is February 21-27. Week 53, which includes only February 28-29, was omitted from consideration. The advantage of the week as a measuring span is that it permits greater detail to be viewed. An added advantage is that the day and week numbers remain the same whether or not there is a leap year. In Table 1 are shown the record periods of the various solar radiation measurements made at St. Paul.

Table 1. The solar radiometer history at St. Paul, 1963-1985.

Radiometer	Radiometer Orientation and Measurement	Beginning Date	Terminal Date	Duration, Months
Pyranometer	a. Horizontal (facing up); incoming radiation	1/1/63	12/31/85	276
"	b. 55° from horizontal & facing south; incoming radiation	9/1/79	8/21/84	64+
"	c. 90° from horizontal & facing south; incoming radiation	8/22/84	12/31/85	16+
"	d. Horizontal (facing down); outgoing (reflected) radiation	11/21/69	12/31/85	192+
"	e. Horizontal (facing up) with occultation ring; diffuse radiation	9/1/77	12/31/85	100
Pyrheliometer	a. Always perpendicular to solar rays; incoming direct beam radiation	7/27/80	12/31/85	65+

DATA QUALITY

Everything was done to insure that the measurements were of high quality. This included daily visits (weekends and holidays included) to clean the radiometer domes as required, and to check the following: (a) the position of the occultation ring so it shaded the radiometer used to measure diffuse radiation, and (b) the pyrheliometer orientation, so it remained aimed at the sun. All pyranometers in use were calibrated twice each year against another held in reserve for that purpose, and the recorders were serviced quarterly.

Pyranometers used to measure incoming solar radiation were also checked for deterioration of the sensors over the long-term. This was done by determining if there was a change in the transmission coefficient of the atmosphere as indicated by the instrument in use at the time. Clear day radiation values are one means of determining atmospheric transmissivity, defined as the ratio of measured solar radiation at the surface of the earth to that received at the outer limit of the earth's atmosphere. The comparison presented in Figure 1 shows that September 20 through October 10 clear-day transmissivity has been virtually constant with time. Thus, it can be accepted that the pyranometers used for the long-term measurement of solar radiation on the horizontal surface during 1963-1985 have not deteriorated. The dates chosen center around the week in the North Central region most likely to have clear days, September 26-October 3, according to a study by Baker <u>et al</u>. (1983).

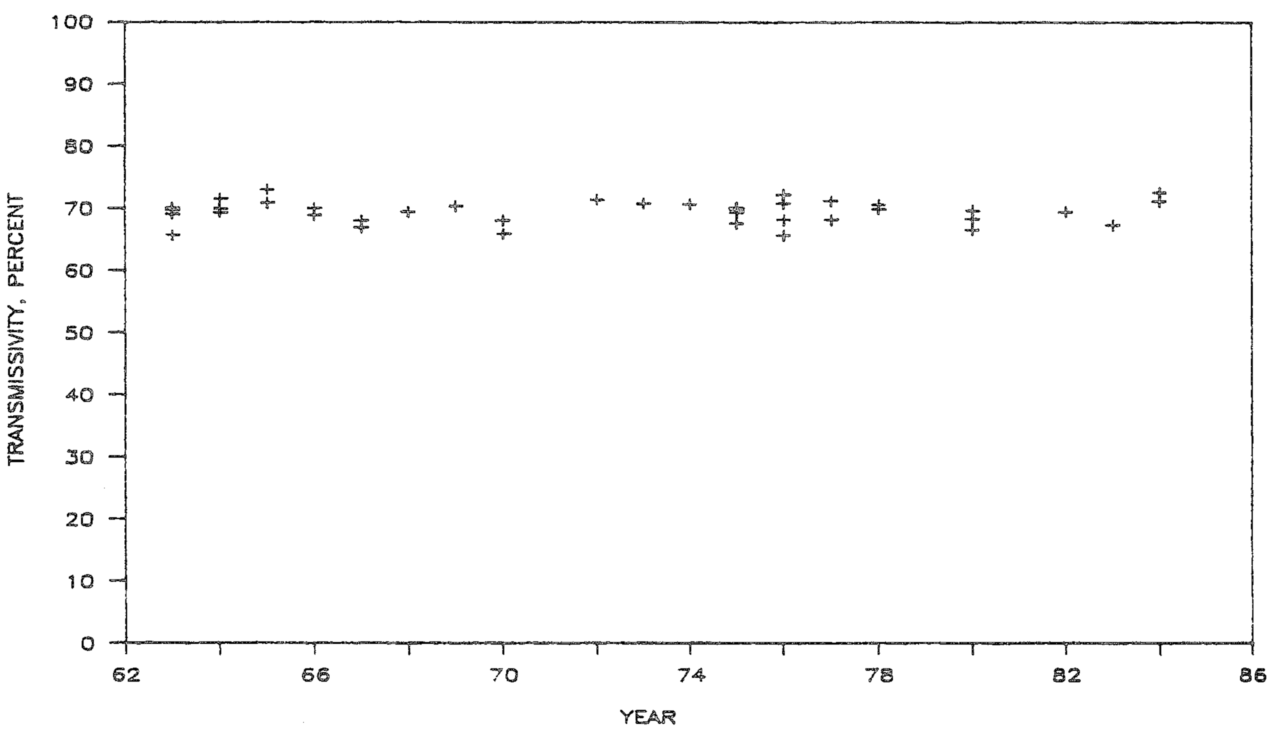

Figure 1. Atmospheric transmissivity values obtained with the pyranometers in use during the 1963-1985 record. Values are based on the measured radiation for clear-days within the period of September 20-October 10, when the probability of clear-days is at a maximum. The days selected had both 100 percent sunshine and 0 tenths cloud cover.

DATA RECONSTRUCTION AND CORRECTION PROCEDURES

The occasional malfunction of equipment or the occurrence of frost or ice on the radiometer domes created days or portions of days for which no data were available. Thus, in order to use the data in this and earlier studies and, in particular, the study dealing with the availability and dependability of solar radiation (Baker and Enz, 1979), a great deal of effort went into completing the incoming total solar radiation record. Three methods were developed to supply these missing data. Missing data for the other measurements were completed where possible but on occasion could not be accurately estimated due to changing surface conditions. The pyrheliometer record contains a proportionally greater amount of missing data because the methods developed to estimate missing values could not be applied to these data. Extended periods of cloudiness reduced the amount of pyrheliometric data and also made alignment of the instrument difficult.

Missing data were estimated by one of three methods: ratio, reconstruction, or regression. Whenever possible, the ratio method was used. In this method the incoming and reflected solar radiation for several days before and several days after the missing day were compared to determine the mean albedo, which is the ratio of reflected solar radiation to the incoming solar radiation expressed as a percentage. Then the solar radiation of the missing day was calculated using the reflected radiation measurement and the mean albedo. When this method could not be used, ratios were developed using either the output of the south-facing 55° from horizontal or the south-facing 90° from horizontal instruments.

When just a portion of the day was missing, the trace of the reflected radiation on the daily chart was used to reconstruct the incoming radiation trace. This portion of the record was then hand integrated and added to that part of the daily record for which the measurement was available.

On those few occasions when neither the ratio nor the reconstruction methods could be used, the regression method was substituted. In this case the value for the missing day was estimated using a weekly linear regression equation with measured solar radiation at the St. Cloud National Weather Service Office Airport (WSO AP) as the dependent variable. This gave the estimated value for radiation at St. Cloud, which was then adjusted for the 78 mi (126 km) distance between St. Cloud and St. Paul. The regression equations were obtained from a publication by Baker and Haines (1969). Results from this present study now permit the use of the Minneapolis-St. Paul WSO AP sunshine data directly to estimate solar radiation at St. Paul. (See the section on Estimating Radiation Reception.)

The incoming solar radiation record is complete with only 1.8 percent of it involving a day or more that required adjustment by the ratio or regression methods.

RADIATION RECEIVED ON A HORIZONTAL SURFACE

Statistics of Radiation

A stable frequency distribution is required for statistical parameters to provide validity. To have a stable distribution, two conditions must be met. One is that the record must be long enough to provide an acceptable measure of the variability which exists. The second, and one not often considered, is the degree of persistence which exists in the data. The persistence, or similarity in weather from day to day, particularly under stagnant or weak circulation periods, reduces the independence of the data. The assumption of independence is common in many inferential and statistical tests and estimates. The lack of independence means that a larger sample must be taken in order to acquire the same information as in a random sample data set.

Few studies have dealt with the required sample size of daily total solar radiation records. Even fewer have considered the persistence effect. One, by Baker and Klink (1975), compared radiation records of stations within the North Central region. They found that a minimum of about six years of daily data was required. A later study by Skaggs et al. (1982) determined the sample size based upon the St. Paul solar radiation data. They considered both the inherent variability of the weather as it affected the radiation plus the effect of persistence of weather conditions. In terms of persistence they found that the characteristic time between independent samples ranged from a maximum of 2.02 days in September to a minimum of 1.29 days in July. Even though atmospheric circulation is at its weakest in July and persistence is seemingly very high, the small scale and nearly random convective patterns and associated cloud cover resulted in a minimum of persistence. The September maximum persistence was a combination of the still remaining weak circulation typical of summer and the time when there is the least temperature contrast between land and ocean surfaces. The latter was responsible in part for the occurrence of nearly cloudless days, with the maximum reached in the week of September 26-October 3 (Baker et al., 1983).

In addition to the intra-month serial correlation there is apparently a persistence introduced by the inter-annual variability of the mean due to multimodal parent populations (Skaggs et al., 1982). That is, there seem to be years which are persistently cloudy as well as years that are relatively clear.

Skaggs et al., (1982) calculated the number of days needed to estimate the true daily mean solar radiation within ± 1.04 MJ/(m^2 day)[± 25 cal/(cm^2 day)] at a confidence level of 95 percent. The results, shown in Table 2, are intended to account both for persistence and for the inherent variability of daily solar radiation values.

The required number of days range from a low of 38 in January (1.2 years) to a high of 455 days (14.7 years) in May. The average for the 12 months is 254 days, equivalent to 8.3 years. Therefore, the 1963-1985 St. Paul solar radiation record is long enough that a stable frequency distribution can be expected, and confidence can be placed in the derived parameters and probabilities.

Table 2. Estimates of the required sample size in days for the true mean to be within ± 1 MJ/(m^2 day)[± 25 cal/(cm^2 day)] 95 percent of the time. (After Skaggs et al., 1982.)

Month	Days	Month	Days
January	38	July	277
February	57	August	446
March	301	September	441
April	307	October	164
May	455	November	93
June	418	December	47

Measures of Central Tendency Measures of central tendency, the mean, median, and mode, Table 3, undergo similar changes during the year, but they seldom coincide. While the mean remains the center of gravity of the data, only in November and December does it separate the monthly distributions into equal parts. Despite the common use of the mean, the median is often a more useful statistic since by definition it separates distributions into two equal parts. The weekly differences between the median and the mean, Figure 2, emphasize the skewness of the radiation values. It is apparent that on a weekly basis only in the late autumn and early winter does the mean come close to separating the values into two equal parts.

Since the month is still the most common summarization period, the various monthly and annual statistical measures of the radiation data at St. Paul were calculated and are listed in Table 3. The much more detailed weekly values can be observed in Table 4.

Table 3. Monthly statistics of the daily total solar radiation record, St. Paul, 1963-1985.

Month	Measures of Central Tendency, MJ/(m^2 day) Mean	Median	Mode	Measures of Dispersion W/m^2 Maximum	Minimum	Range	Std. Dev.	Std. Error of Mean	Percent Coeff. of Var.	Measures of Distribution Coefficients of Skewness	Kurtosis
Jan.	6.58	7.12	8.29	11.68	0.42	11.26	2.56	0.10	38.9	-0.34	-0.78
Feb.	9.98	10.76	(1)	17.83	0.29	17.54	3.84	0.15	38.4	-0.45	-0.71
Mar.	13.32	14.90	(2)	25.03	0.92	24.11	6.00	0.22	45.0	-0.36	-1.15
Apr.	16.10	17.16	23.65	28.84	0.33	28.51	7.69	0.29	47.8	-0.30	-1.22
May	19.87	21.98	(3)	31.60	1.30	30.31	7.89	0.30	39.7	-0.54	-0.93
June	21.74	23.61	26.79	32.90	1.67	31.23	7.13	0.27	32.8	-0.63	-0.65
July	22.58	24.03	26.62	31.98	4.14	27.84	5.94	0.22	26.3	-1.00	0.31
Aug.	18.84	20.72	(4)	28.34	2.22	26.12	6.40	0.24	34.0	-0.76	-0.48
Sept.	14.12	15.74	(5)	23.52	1.05	22.48	6.06	0.23	42.9	-0.51	-1.03
Oct.	9.47	10.46	15.86	18.79	0.38	18.42	4.60	0.17	48.6	-0.26	-1.13
Nov.	5.71	5.65	9.00	12.18	0.04	12.14	3.10	0.12	54.3	0.12	-1.09
Dec.	4.78	4.81	7.53	9.13	0.04	9.08	2.36	0.08	49.4	-0.05	-1.28
Ann.	13.61	12.14	(6)	32.90	0.04	32.86	8.27	0.09	80.8	0.34	-1.09

(1) 10.76, 14.32
(2) 16.49, 17.71, 18.63
(3) 26.33, 26.41, 27.17, 28.80
(4) 23.69, 23.98
(5) 17.50, 17.54
(6) 6.61, 7.74

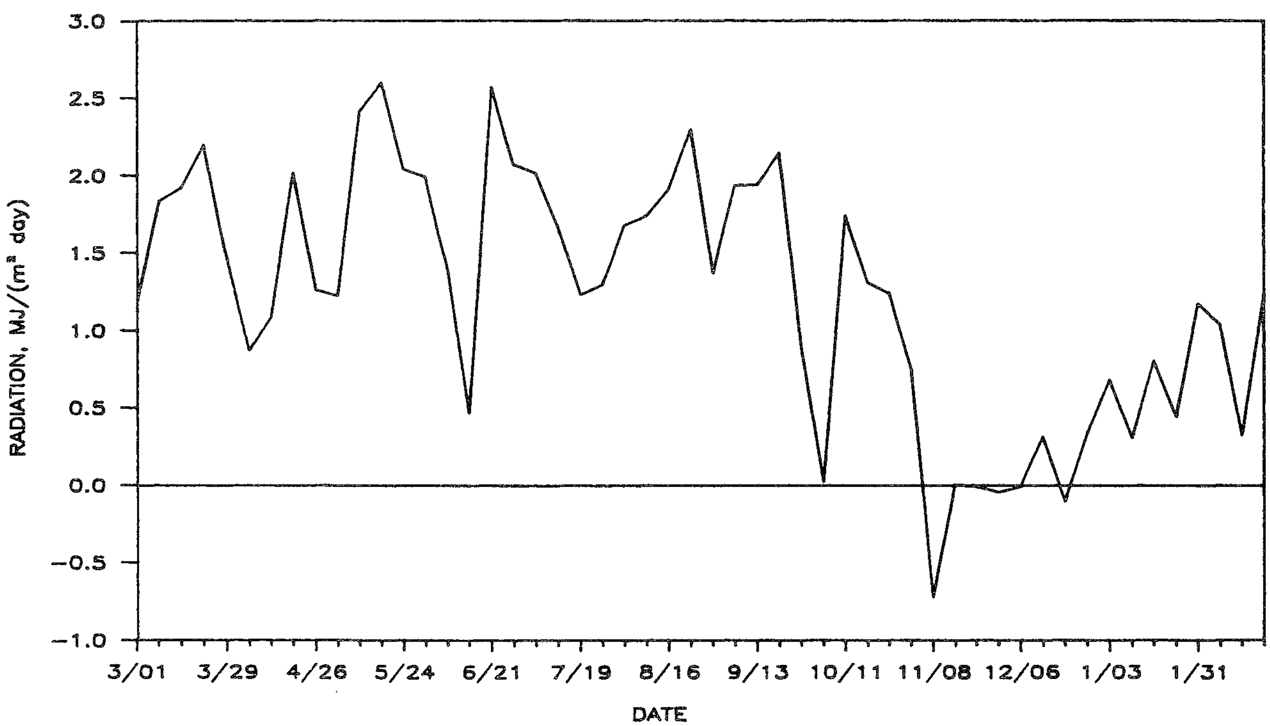

Figure 2. The difference between the median and the mean daily total solar radiation for each climatological week at St. Paul, 1963-1985. Positive values indicate the median is greater than the mean.

Table 4. Weekly statistics of the daily total solar radiation, St. Paul, 1963-1985.
Units are MJ/(m^2 day) except as noted. The number of daily values in each week is 161.

CLIM WEEK	FIRST DATE	MEAN	MEDIAN	MODE	MAX	MIN	RANGE	STD DEV	COEF VAR (1)	STD ERROR	SKEWNESS (2)	KURTOSIS (2)
1	3/01	11.45	12.64	17.2	18.63	0.92	17.71	5.38	47.0	0.42	-0.40	1.75
2	08	13.15	14.99	*	20.64	1.72	18.92	5.43	41.3	0.43	-0.49	1.89
3	15	13.40	15.32	18.4	21.68	1.30	20.39	6.18	46.1	0.49	-0.38	1.66
4	22	14.75	16.95	17.6/19.7	23.44	1.59	21.85	6.07	41.2	0.48	-0.61	2.07
5	29	14.64	16.12	21.5/22.9	25.03	2.09	22.94	7.03	48.0	0.55	-0.33	1.73
6	4/05	15.79	16.66	23.6/23.7	25.78	0.84	24.95	7.01	44.4	0.55	-0.33	1.71
7	12	15.19	16.28	23.5	27.00	2.30	24.70	7.70	50.7	0.61	-0.24	1.69
8	19	17.23	19.25	*	28.34	1.05	27.29	8.19	47.5	0.65	-0.42	1.75
9	26	18.00	19.25	26.5	28.88	0.33	28.55	7.94	44.1	0.63	-0.44	1.97
10	5/03	19.79	21.01	*	29.43	2.97	26.45	7.42	37.5	0.58	-0.54	2.08
11	10	19.06	21.47	27.0	30.43	1.30	29.13	8.30	43.5	0.65	-0.50	1.87
12	17	20.54	23.15	27.7/30.0	30.51	1.67	28.84	7.89	38.4	0.62	-0.64	2.23
13	24	20.15	22.19	22.0	31.60	1.38	30.22	8.06	40.0	0.63	-0.50	2.09
14	31	22.04	24.03	18.6	32.65	1.67	30.98	7.06	32.0	0.56	-0.68	2.48
15	6/07	21.43	22.81	18.8/30.1	32.90	3.85	29.05	7.30	34.1	0.58	-0.59	2.34
16	14	20.97	21.43	22.6	31.60	5.19	26.41	6.84	32.6	0.54	-0.40	2.08
17	21	21.74	24.32	*	32.52	3.60	28.92	7.59	34.9	0.60	-0.65	2.25
18	28	23.80	25.87	29.8	31.98	3.98	28.00	6.21	26.1	0.49	-1.14	3.68
19	7/05	23.52	25.53	26.6	31.52	4.81	26.71	6.08	25.8	0.48	-1.33	4.10
20	12	22.11	23.78	27.4	30.43	5.23	25.20	6.02	27.2	0.47	-0.99	3.12
21	19	22.71	23.94	*	31.31	7.24	24.07	5.65	24.9	0.45	-0.96	3.15
22	26	20.84	22.14	22.3	29.01	5.65	23.36	5.58	26.7	0.44	-0.78	2.95
23	8/02	21.38	23.06	23.7	28.34	3.81	24.53	5.29	24.7	0.42	-1.12	3.72
24	09	20.27	22.02	24.5/24.7	28.00	2.89	25.12	5.72	28.2	0.45	-1.03	3.25
25	16	18.13	20.05	*	26.79	2.93	23.86	6.25	34.5	0.49	-0.61	2.21
26	23	16.20	18.50	21.5	25.99	2.22	23.78	6.83	42.1	0.54	-0.48	1.83
27	30	16.63	18.00	21.6	23.69	3.31	20.39	5.53	33.2	0.44	-0.65	2.22
28	9/06	15.22	17.16	*	22.73	1.97	20.76	5.94	39.0	0.47	-0.67	2.08
29	13	13.67	15.61	19.5	21.98	1.30	20.68	6.12	44.8	0.48	-0.44	1.73
30	20	12.50	14.65	*	21.52	1.05	20.47	6.07	48.6	0.48	-0.45	1.66
31	27	12.18	13.06	17.5	18.79	1.13	17.66	4.97	40.8	0.39	-0.56	2.09
32	10/04	9.98	10.00	15.9	16.74	0.88	15.86	4.98	49.9	0.39	-0.23	1.60
33	11	9.72	11.47	13.6/14.6	15.82	1.55	14.27	4.65	47.8	0.37	-0.49	1.68
34	18	8.53	9.84	*	15.32	0.75	14.57	4.31	50.5	0.34	-0.28	1.63
35	25	8.31	9.54	12.3	14.32	0.38	13.94	3.71	44.7	0.29	-0.58	2.12
36	11/01	7.12	7.87	9.0/10.8	12.18	0.63	11.55	3.43	48.1	0.27	-0.26	1.85
37	08	5.58	4.86	4.9/ 9.3	11.13	0.04	11.09	3.27	58.5	0.26	0.13	1.64
38	15	5.35	5.36	8.5	10.13	0.29	9.84	2.80	52.4	0.22	-0.03	1.70
39	22	4.95	4.94	8.4	9.75	0.54	9.21	2.58	52.1	0.20	0.03	1.67
40	29	4.82	4.77	*	9.13	0.04	9.08	2.35	48.9	0.19	0.05	1.84
41	12/06	4.78	4.77	7.5	8.37	0.59	7.79	2.18	45.7	0.17	-0.08	1.79
42	13	4.87	5.19	1.5	8.33	0.67	7.66	2.28	46.8	0.18	-0.19	1.69
43	20	4.71	4.60	7.0	8.41	0.75	7.66	2.25	47.7	0.18	-0.03	1.57
44	27	5.10	5.44	7.7	8.71	0.54	8.16	2.30	45.1	0.18	-0.21	1.70
45	1/03	5.93	6.61	8.4	9.29	0.84	8.46	2.25	37.9	0.18	-0.55	2.10
46	10	6.18	6.49	*	9.79	0.42	9.38	2.29	37.0	0.18	-0.38	2.20
47	17	6.69	7.49	8.3	10.59	1.30	9.29	2.53	37.9	0.20	-0.51	2.08
48	24	7.51	7.95	10.6	11.55	0.84	10.72	2.72	36.2	0.21	-0.61	2.34
49	31	8.83	10.00	12.1	12.93	1.34	11.59	3.14	35.6	0.25	-0.74	2.36
50	2/07	9.52	10.55	12.9	14.44	1.51	12.93	3.30	34.7	0.26	-0.68	2.26
51	14	9.64	9.96	14.1/14.8	15.19	0.96	14.23	3.81	39.5	0.30	-0.31	1.94
52	21	11.41	12.64	14.3/15.2	17.83	0.29	17.54	4.28	37.5	0.34	-0.93	2.78

* Indicates multi-modal (1) Expressed in percent (2) Dimensionless

Measures of Dispersion The absolute maximum monthly values, Table 3, and weekly values, Figure 3 and Table 4, can be accepted as the highest values to be expected. It is unlikely that future values would be much more than those recorded to date. The plot of these values exhibits the regular rise and fall associated with the annual passage of the earth around the sun. Neither the monthly, Table 3, nor the weekly, Figure 3 and Table 4, minimum values show such a regular pattern. Rather, the minimum is more or less uniformly low until the May-September period with the largest minimum occurring in July. This can be attributed in part to the combination of longer days and higher sun during the May-September period. Another factor is a change in the character of the weather systems during this period. Rather than intense low pressure weather systems that often produce extensive and persistent cloud cover typical of late autumn and early winter in the North-Central region, there is another and quite different weather type common during the warm period of the year. This is the more localized convective type system which reaches its peak frequency in July. As a result, extended periods of cloud cover are relatively rare, as indicated by the higher mid-summer radiation minima in Figure 3.

The minimum values listed in Table 3 are considerably lower, in terms of the fraction of radiation transmitted through the atmosphere, than the values given by List (1958) for particular cloud types. Our numbers represent what might be considered as the lowest likely to occur. On these days of extremely low incoming radiation, the record invariably indicated a day with a thick overcast of nimbostratus, a cloud with which precipitation is associated. Fog and haze were sometimes reported also.

The standard deviation measures absolute dispersion and has special significance when applied to normal distributions. The skewed distributions of solar radiation data prevent the standard deviation from serving in its usual capacity as a predictor of population distributions. The maximum standard deviation, Table 3, occurs in May, followed by April. The minimum occurs in December, with January a close second. This is a further indication of the annual cycle found in almost all radiation statistics, although in this case the maximum deviation is thrown slightly out of phase with a May rather than a June maximum. March and October serve as the solar radiation transition months between the months of November through February, the low standard deviation period, and the high standard deviation months of April through September. The deviations are greatest in April thru June.

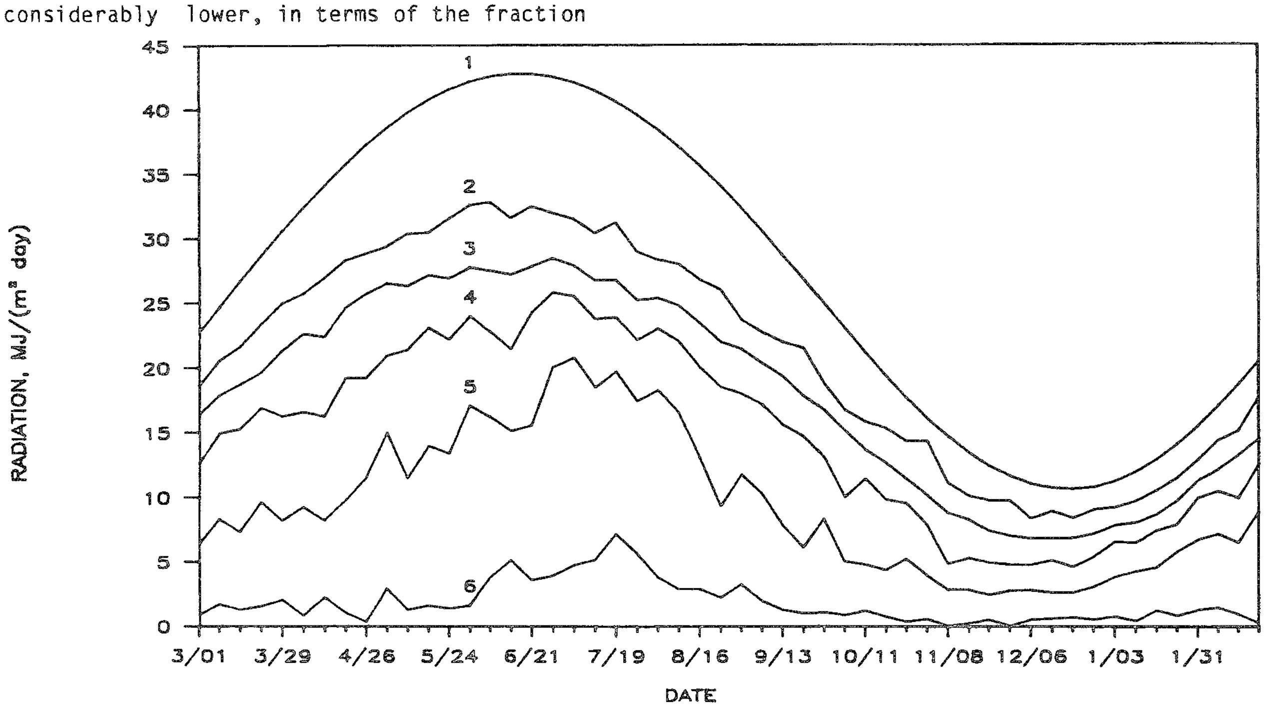

Figure 3. Mean daily total solar radiation received on a horizontal surface under six different conditions for each climatological week: (1) in the absence of an atmosphere (extraterrestrial radiation), (2) maximum radiation, (3, 4, 5) radiation received with a probability of 25, 50 and 75 percent, respectively, and (6) minimum radiation, St. Paul, 1963-1985.

The periods of maximum standard deviation are associated with months that have both high radiation potentials and large daily variations in cloud cover. Small standard deviations are associated with months of low potential radiation and persistent, and frequently total, cloud cover. The coefficient of variation, the ratio of the standard deviation to the mean, Table 3, shows a minimum in July and a maximum in November, indicating that in relative terms the radiation variation is much greater in November. This is much more clearly demonstrated by considering the weekly values of each as given in Figure 4 and Table 4.

A more extreme variation in standard deviations is found in the weekly values, Figure 4 and Table 4. Large deviations are found that extend from March 29 to June 27. A secondary maximum extends from August 16 to September 26. These two maxima are associated with a combination of high potential radiation, and rapid and large daily changes in cloud cover that produce daily variations in the solar radiation received. A weak minimum in the standard deviations occurs between the two maxima. It is centered on July 19. This minimum period is associated with the midsummer decrease in both precipitation and associated cloud cover that is a common July to mid-August occurrence. In this regard it is interesting to note the high degree of coincidence between the standard deviations in Figure 4 and the weekly precipitation probabilities at St. Paul, Figure 5.

The primary minimum in standard deviation values is found to extend, on the average, from December 6 to January 16. This period coincides closely with the time of minimum potential radiation and highest frequency of 8/10 or more cloud cover. Together they act to reduce the absolute variation in daily radiation.

Two interesting points in terms of variation in daily radiation are shown in the coefficient of variation values, Figure 4. One is that when the standard deviation is nearing a minimum in late autumn, the coefficient of variation is at a maximum. In contrast to this there is a second coefficient of variation maximum in the spring that coincides in part with the period when standard deviations are reaching a maximum. Its importance is that in both absolute and relative terms the variation in daily radiation is high in the spring. However, in late fall and early winter, while the variation in absolute terms is small, it is large in relative terms.

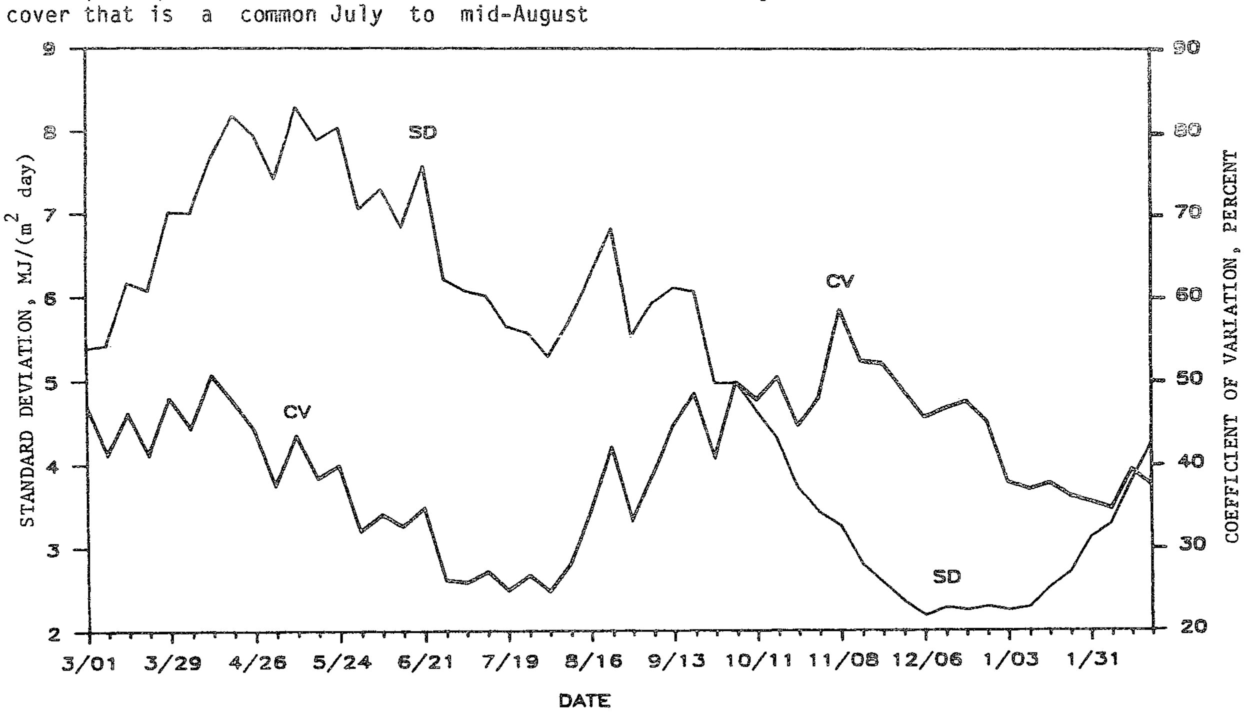

Figure 4. Mean weekly values of the standard deviation (SD; left scale) and coefficient of variation (CV; right scale) of the daily total solar radiation, St. Paul, 1963-1985.

Measures of Distribution Monthly frequency distributions of the daily radiation totals show a range highly dependent on both maximum possible radiation value and cloud cover characteristics. The two extremes are July and December, Figure 6. In winter the short day, low sun, and greater cloud cover combine to give a very small range in values. The expanding scale of radiation values is very apparent in progressing from December to June. With the decreasing amount of cloud cover as summer approaches, it is easy to see why a skewed distribution occurs. July provides the best example of the skewed summer distribution. Actual values for the degree of skewness for each month are listed in Table 3. Only November fails to show a negative skewness; that is, a frequency distribution in which high values are more common than low values.

The frequency distribution of daily total solar radiation for the entire 1963-1985 period, Figure 6, is positively skewed in contrast to all months except November. This seeming paradox occurs in part because there are 3 months when the radiation never exceeded 12.56 MJ/(m^2 day)[300 cal/(cm^2 day)], November-January, and two months when it never exceeded 18.84 MJ/(m^2 day)[450 cal/(cm^2 day)], February and October. These are sufficient to outweigh the other seven months, which, in spite of relatively strong negative skewness, do contribute some low radiation days to the annual distribution.

With the exception of July, monthly distributions are all platykurtic, as is the annual distribution. This distribution of values is somewhat flatter than a normal distribution. There are fewer values in the tails and near the central value (the mean) but more in the intermediate regions of the distribution.

Monthly values of skewness and kurtosis are listed in Table 3. Weekly values are illustrated in Figure 7 and listed in Table 4. The greater detail possible with a weekly analysis shows that kurtosis is negative compared to a normal distribution, and that it is relatively constant except for a brief midsummer period between June 28 and August 15. During this mid-summer period the negative skewness is at a maximum and the weekly distributions depart most from a normal one.

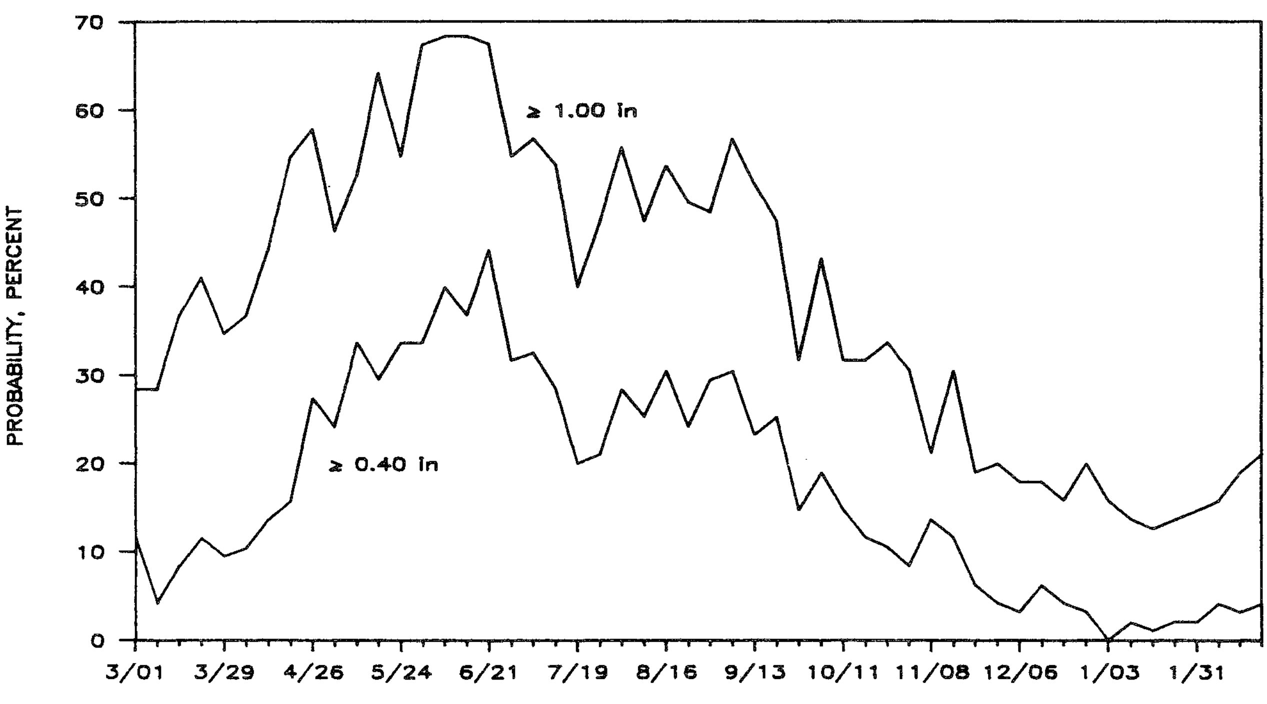

Figure 5. Probability in percent that the weekly total precipitation at St. Paul equals at least 0.40 in (1.00 cm) and 1.00 in (2.54 cm).

Marked changes occur in both weekly and monthly frequency distributions during the course of a year. The changes result from variation in the primary and secondary radiation controls. For a given place on the earth the primary control is the latitude of the station relative to the latitude at which rays of the sun are perpendicular to the surface of the earth and is determined by the time of year. This control establishes the potential radiation value, which is the extraterrestrial radiation. The secondary control is the atmosphere, with the clouds in it exerting the major effect. Thus, the radiation limits are established by the primary control while the shape within any given period is determined by the cloud cover characteristics.

The monthly distributions of daily radiation totals shown in Figure 6 exhibit a bimodal character between September and March. This is most strongly developed in December when cloud cover is at its highest frequency. The radiation mode with the higher frequency is always the one at the higher end of the radiation scale. The lower mode disappears during June, July, and August when cloud cover is least, resulting in a marked negative skewness of the monthly radiation distributions. There is a definite peak in cloud cover amount at St. Paul beginning in late October that lasts until early January. This is when the bimodal character of solar radiation is strongest, with the best example in December. Two kinds of December days create this feature: very cloudy days and days that are relatively free of clouds. In the former the radiation mode is centered around 2.09 MJ/(m^2 day)[50 cal/(cm^2 day)] and in the latter it is centered at about 7.33 MJ/(m^2 day)[175 cal/(cm^2 day)] as shown in Figure 6.

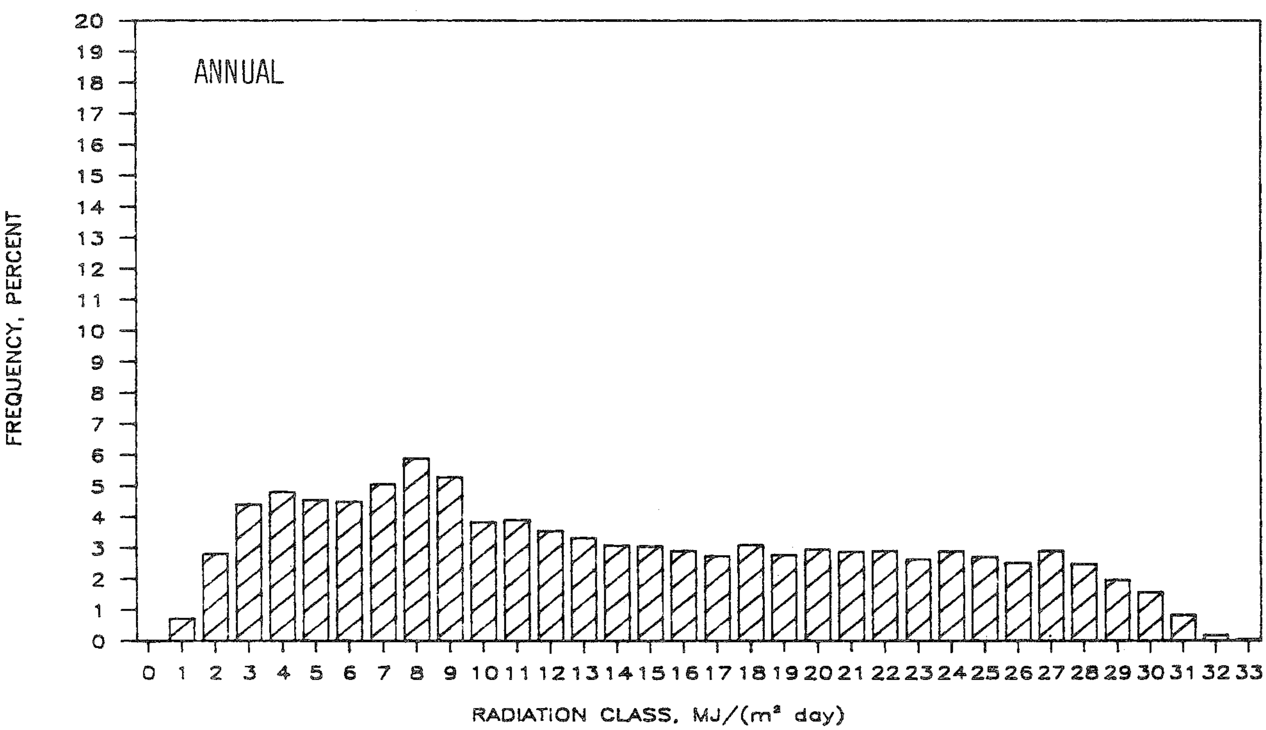

Figure 6. Annual frequency distribution of daily total solar radiation, St. Paul, 1963-1985.

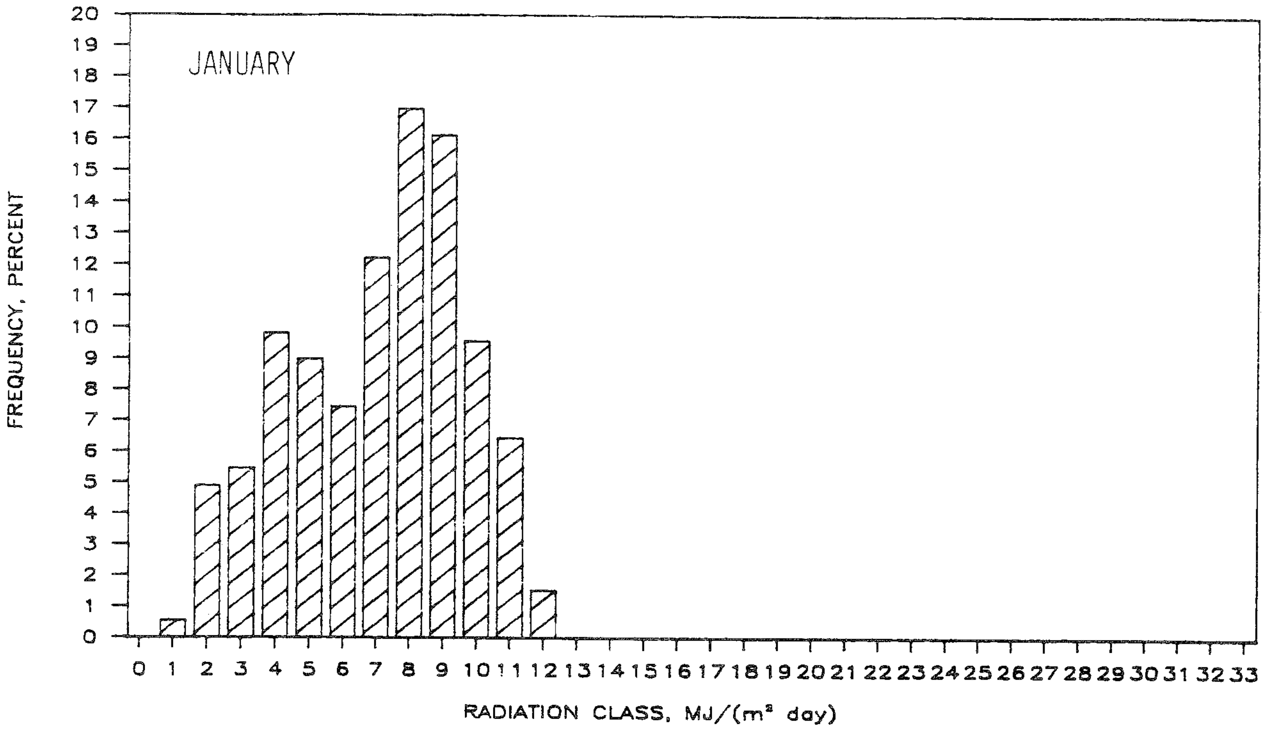

Figure 6. Frequency distribution of daily total solar radiation for January, St. Paul, 1963-1985.

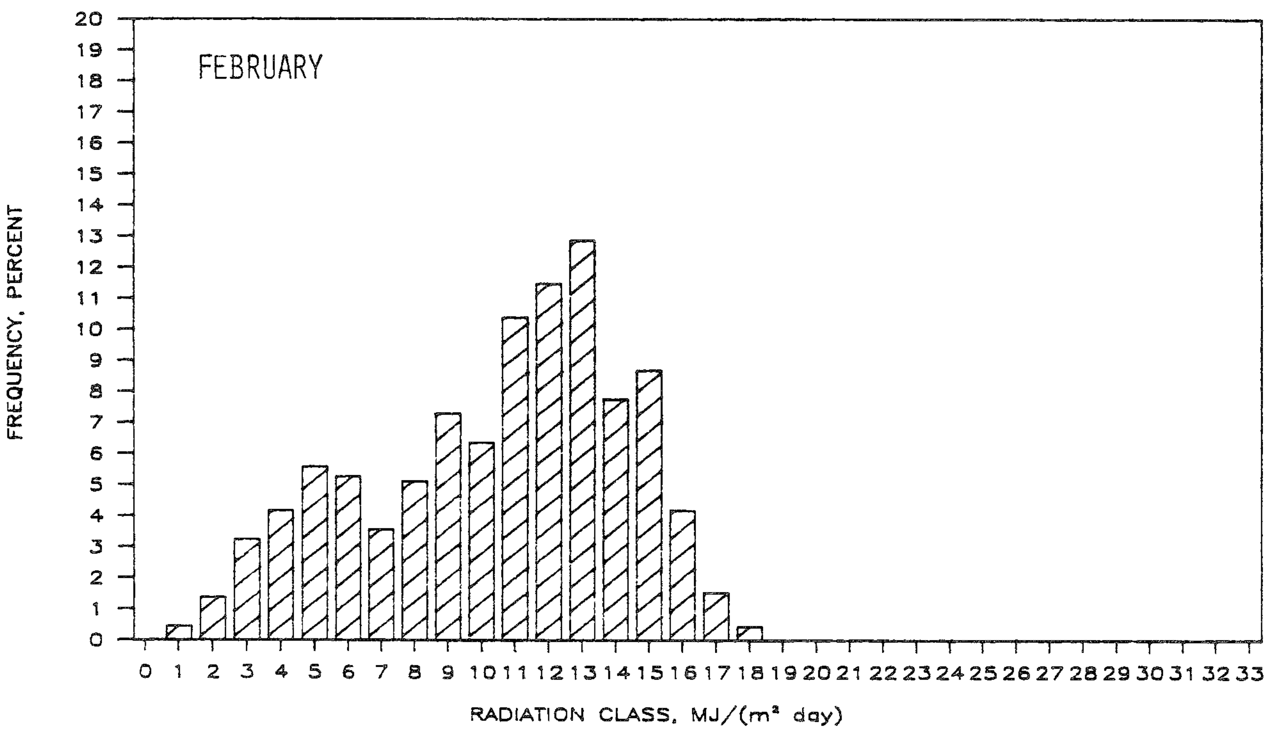

Figure 6. Frequency distribution of daily total solar radiation for February, St. Paul, 1963-1985.

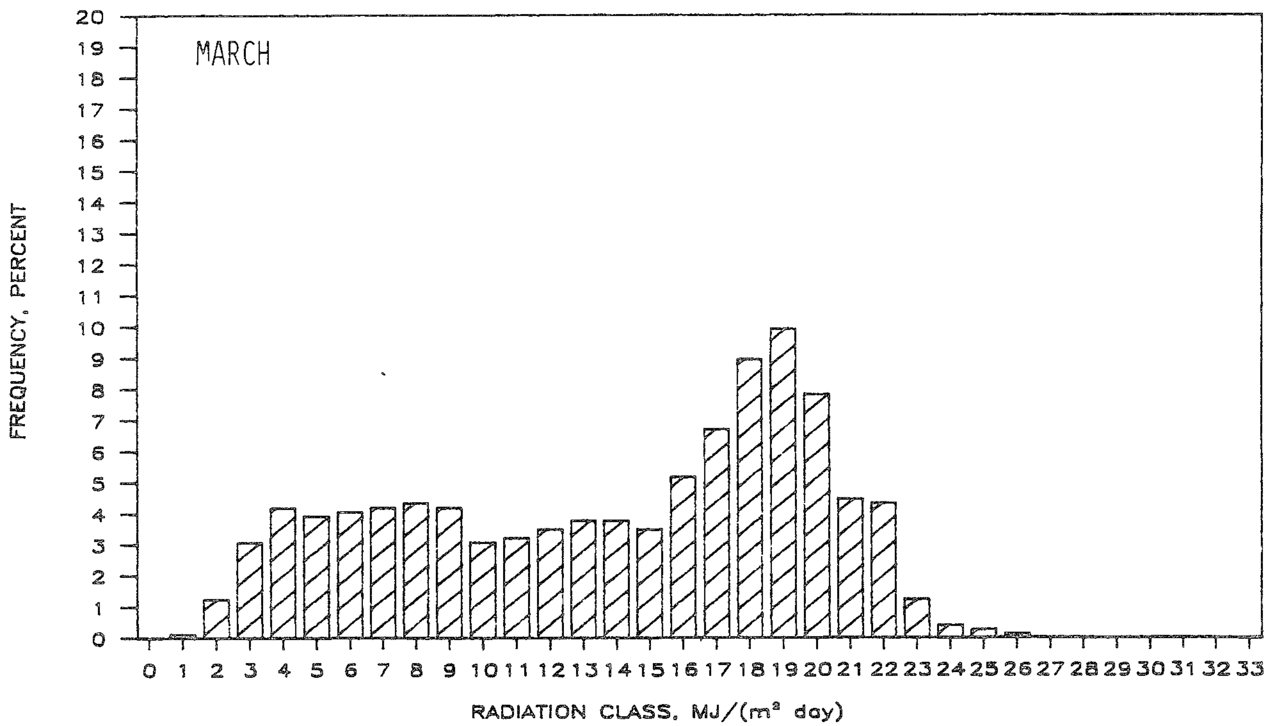

Figure 6. Frequency distribution of daily total solar radiation for March, St. Paul, 1963-1985.

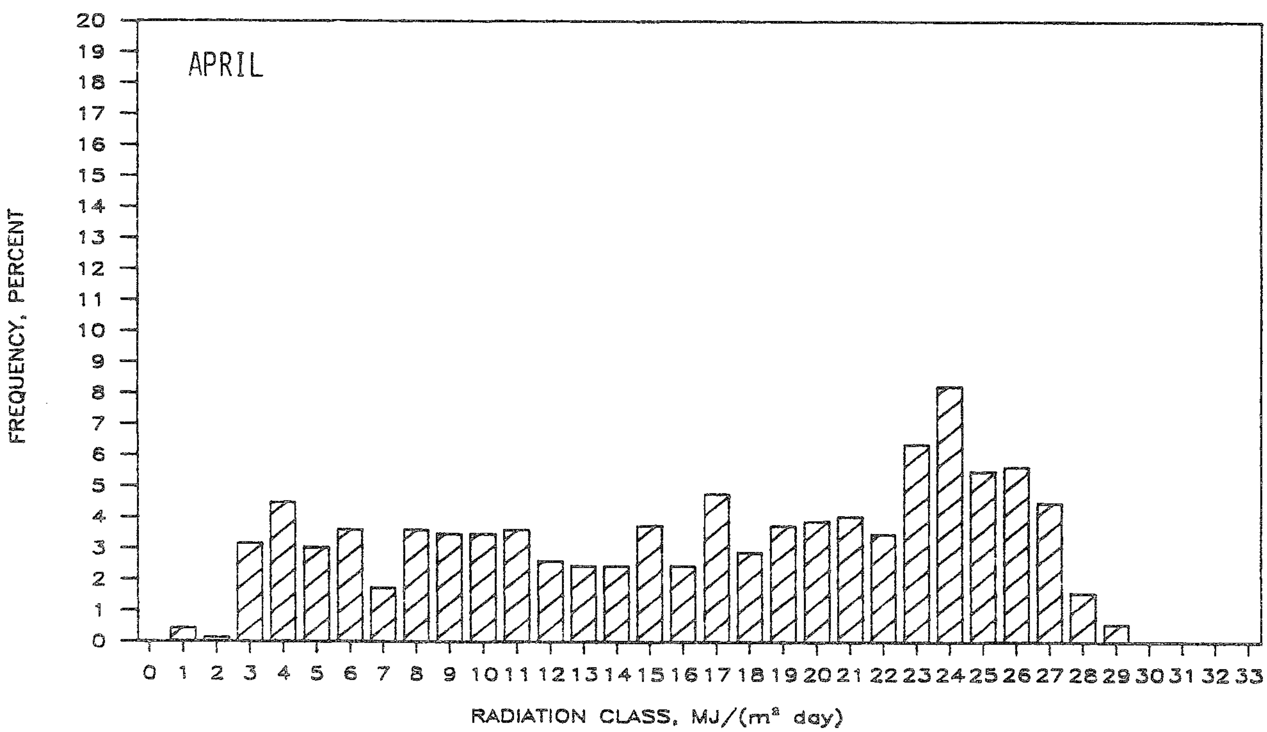

Figure 6. Frequency distribution of daily total solar radiation for April, St. Paul, 1963-1985.

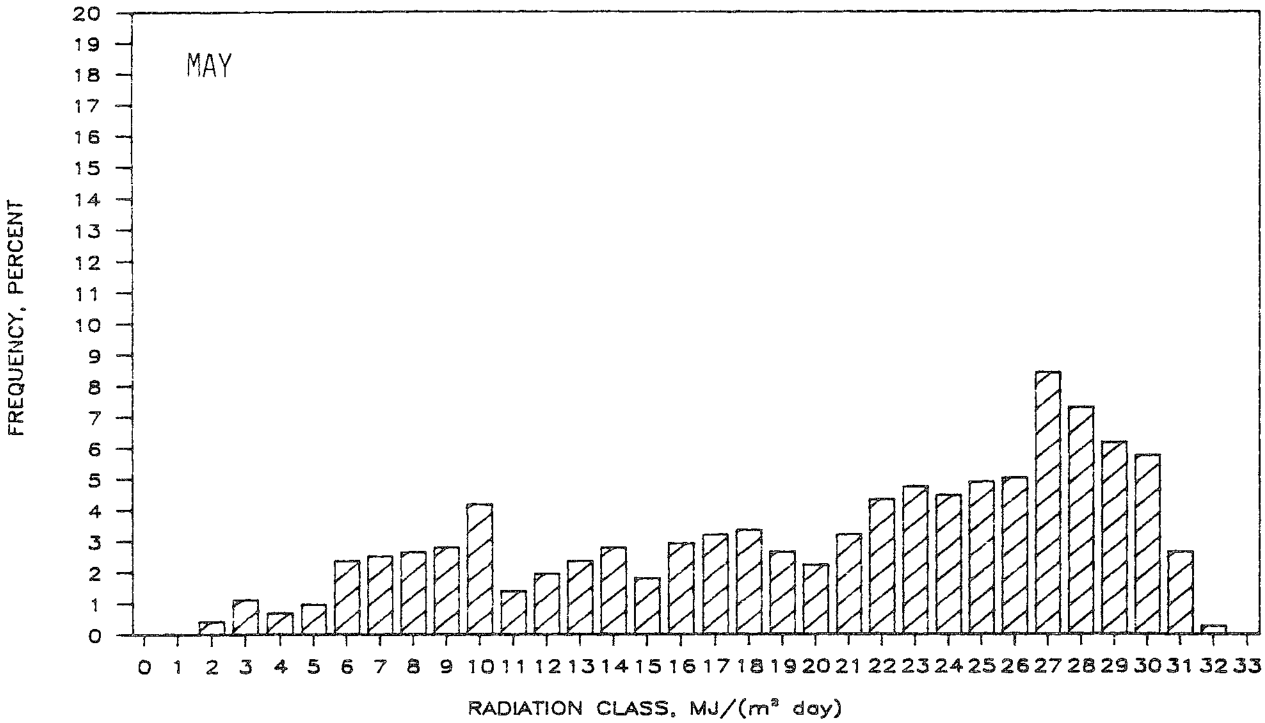

Figure 6. Frequency distribution of daily total solar radiation for May, St. Paul, 1963-1985.

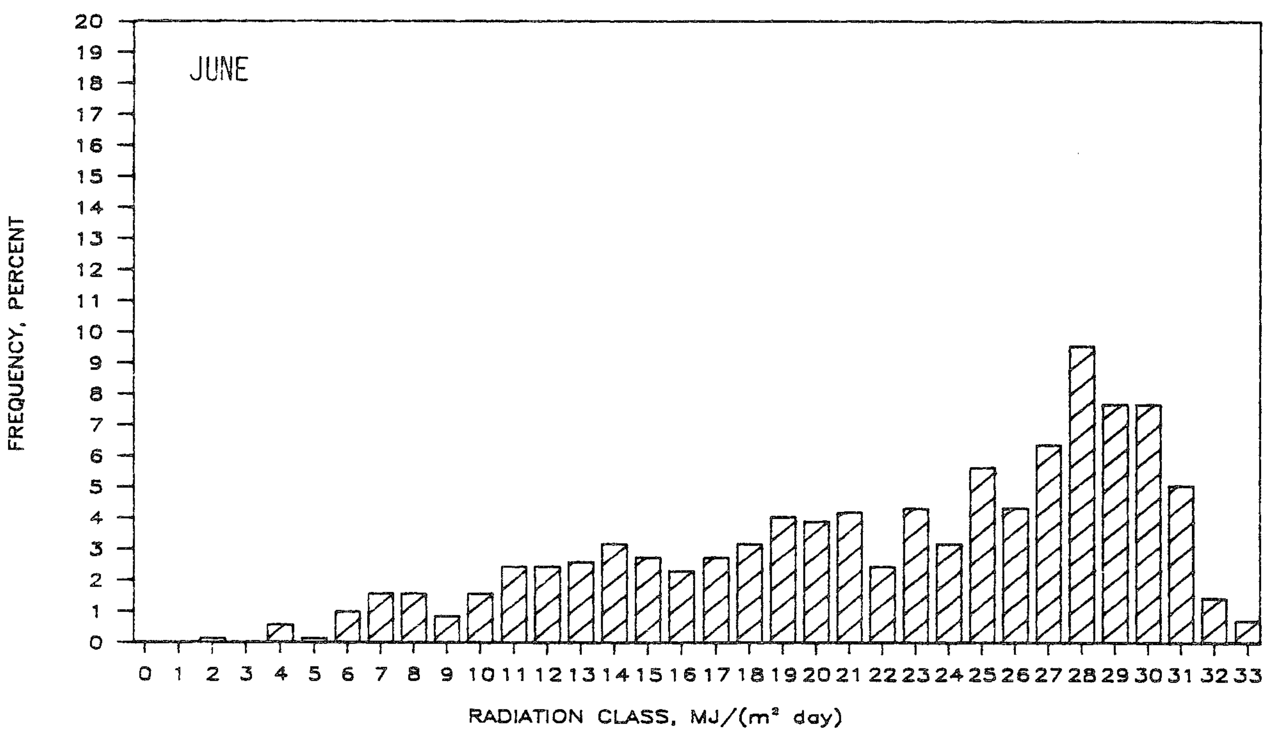

Figure 6. Frequency distribution of daily total solar radiation for June, St. Paul, 1963-1985.

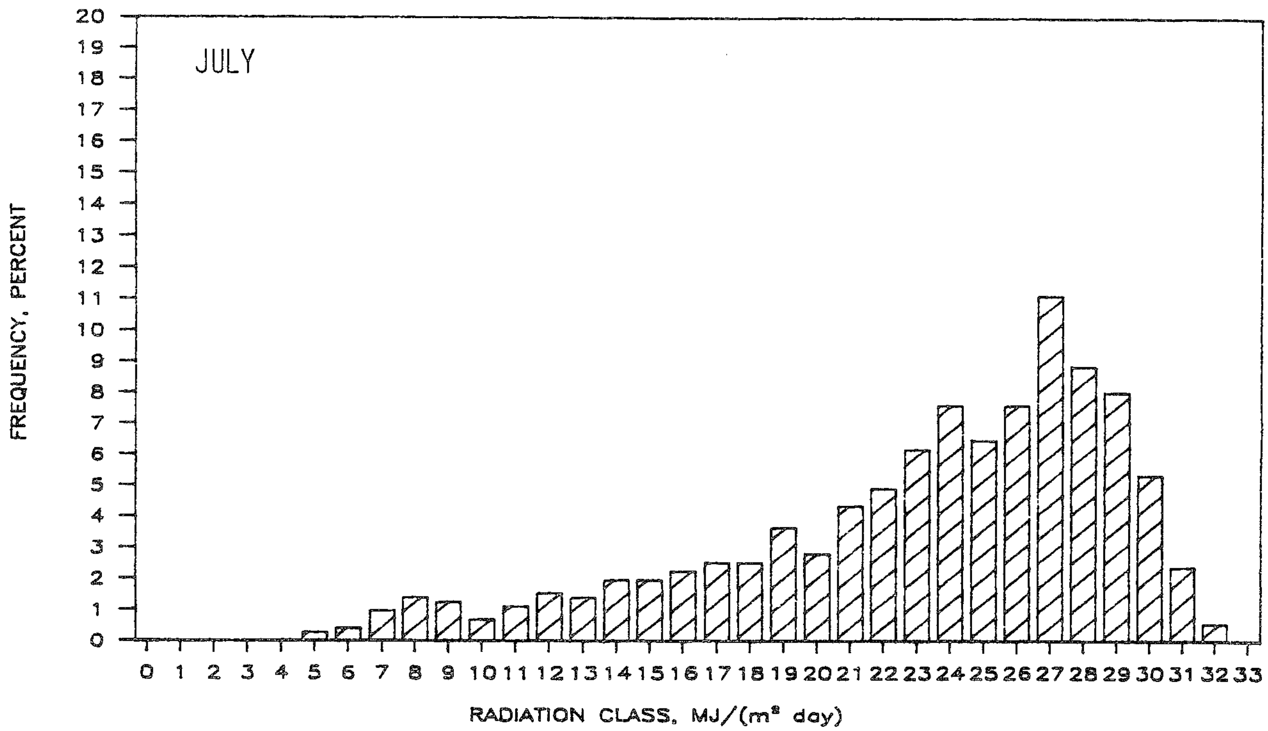

Figure 6. Frequency distribution of daily total solar radiation for July, St. Paul, 1963-1985.

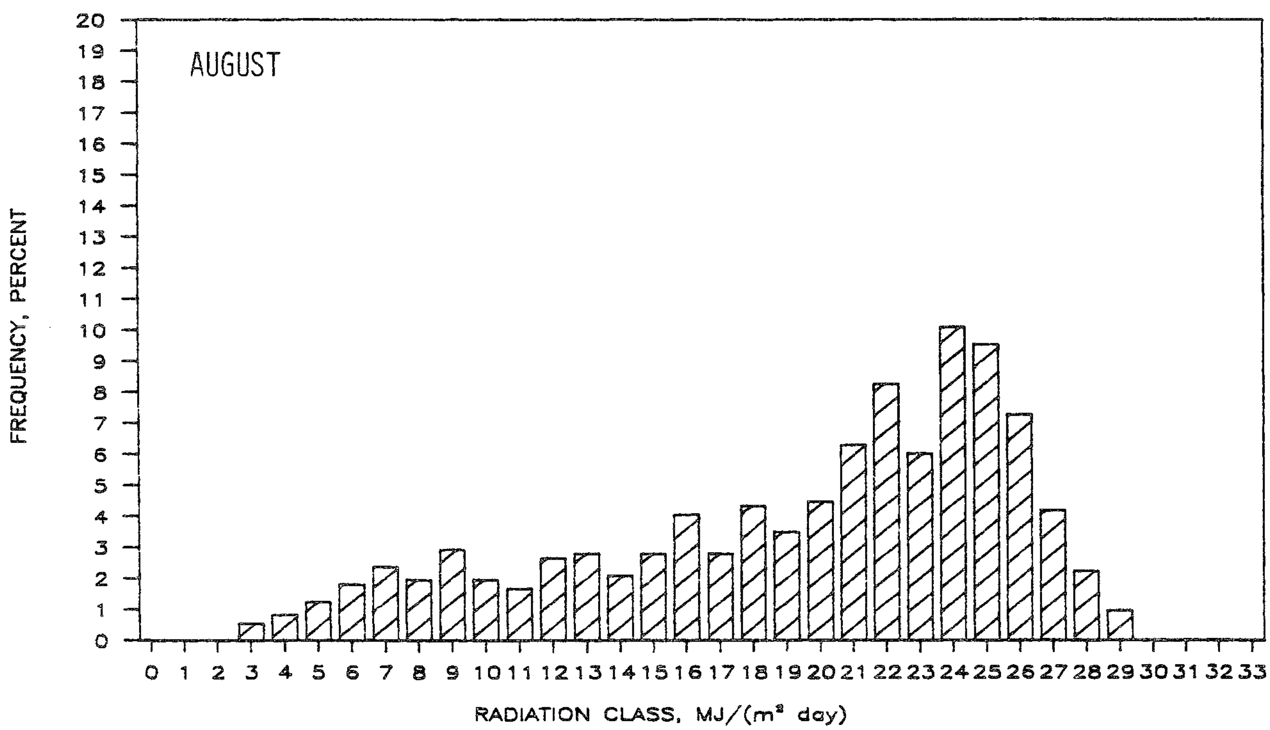

Figure 6. Frequency distribution of daily total solar radiation for August, St. Paul, 1963-1985.

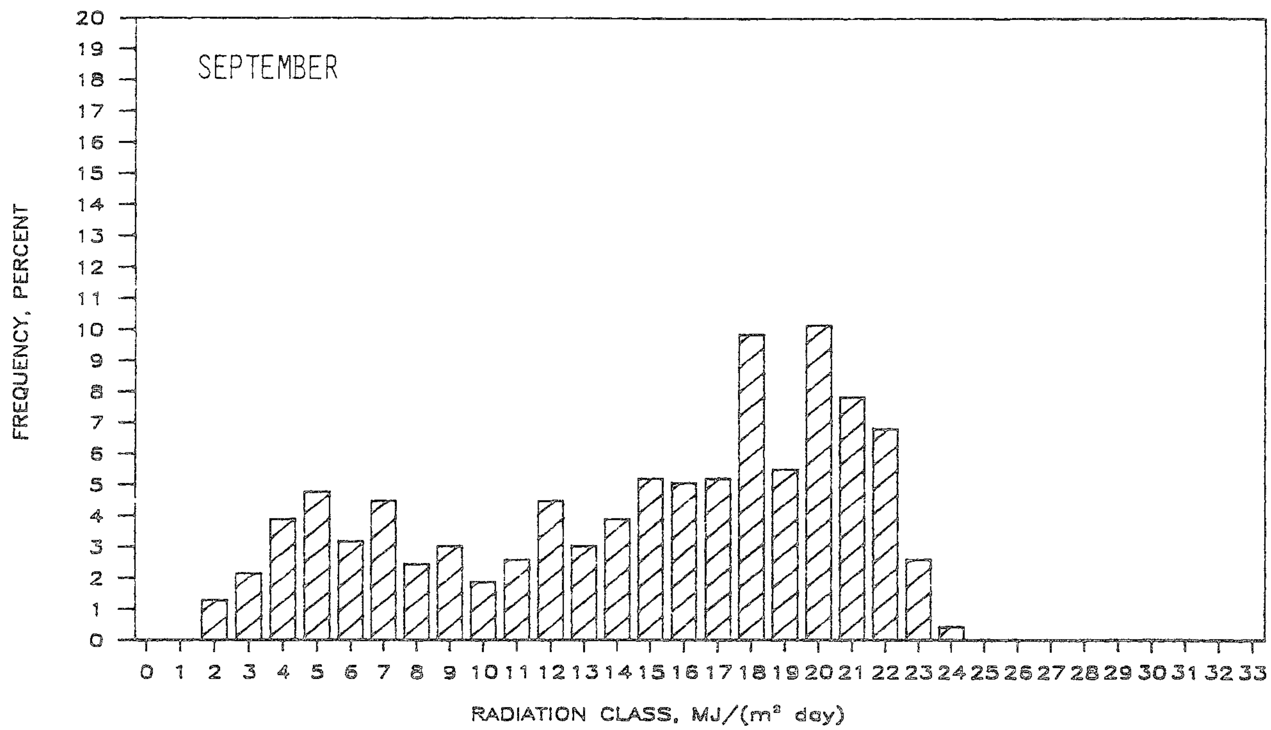

Figure 6. Frequency distribution of daily total solar radiation for September, St. Paul, 1963-1985.

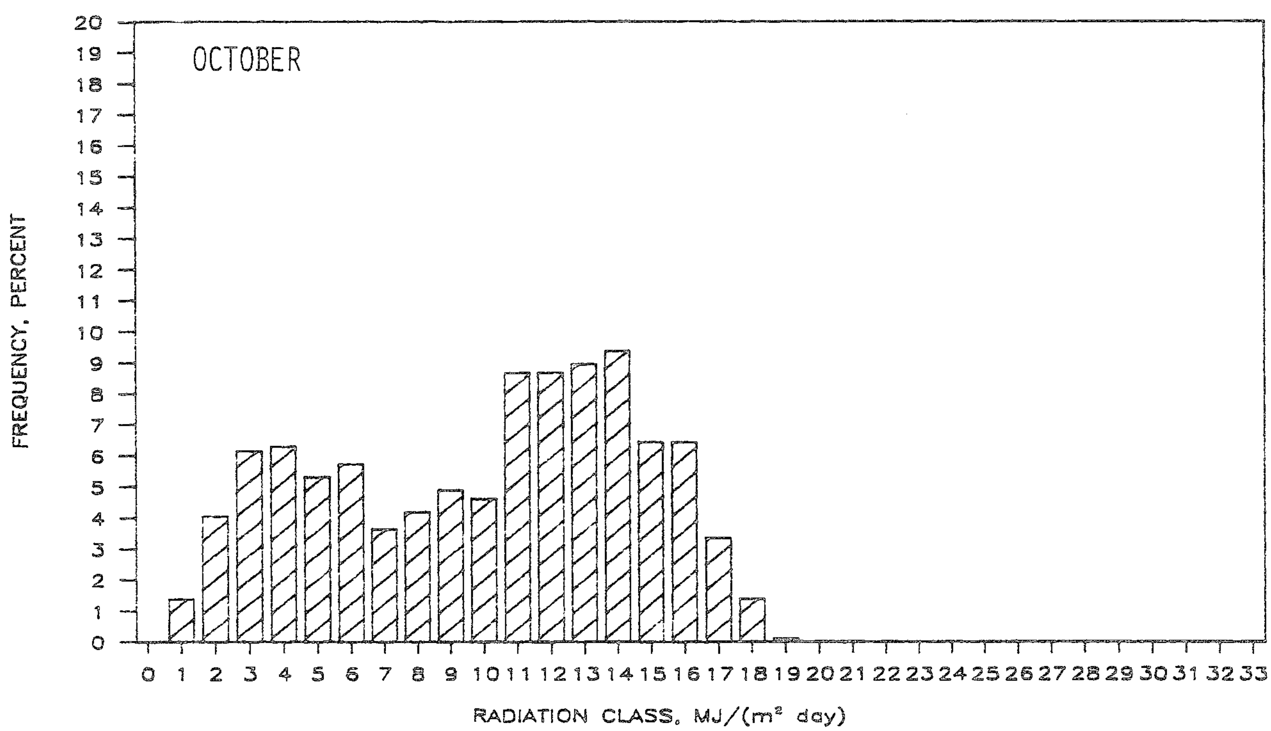

Figure 6. Frequency distribution of daily total solar radiation for October, St. Paul, 1963-1985.

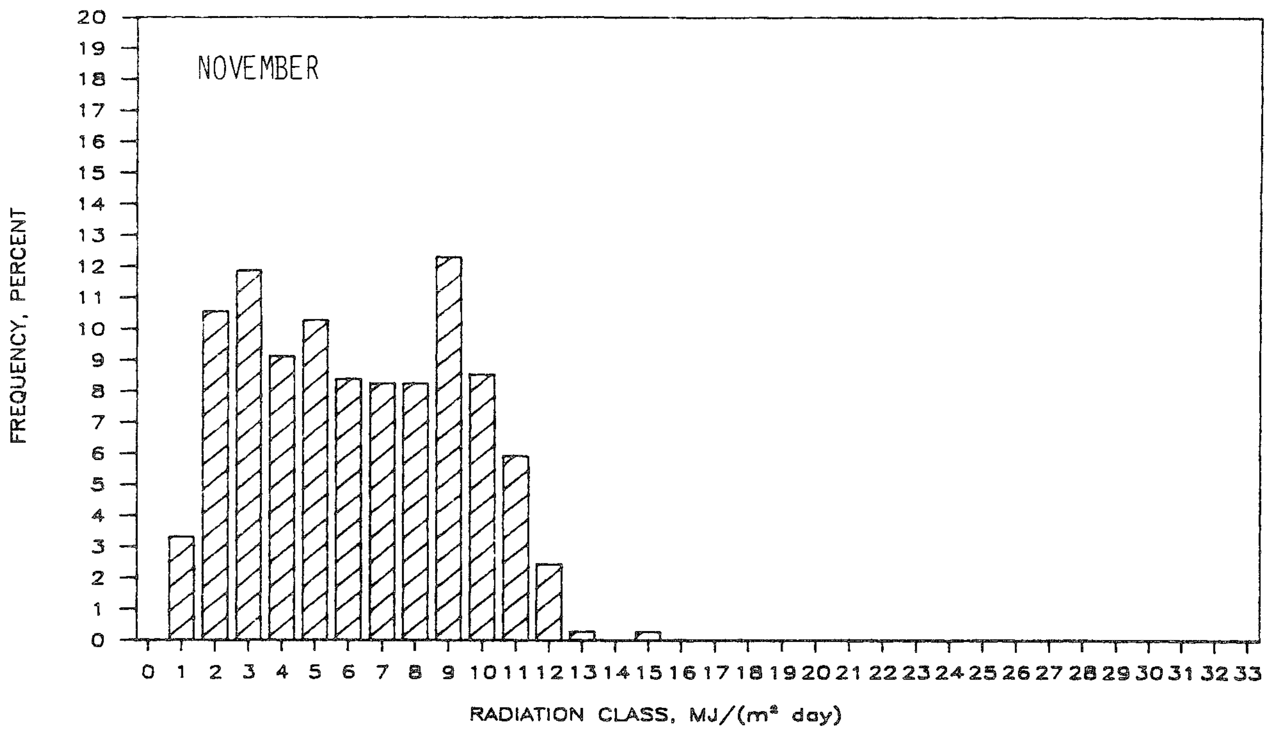

Figure 6. Frequency distribution of daily total solar radiation for November, St. Paul, 1963-1985.

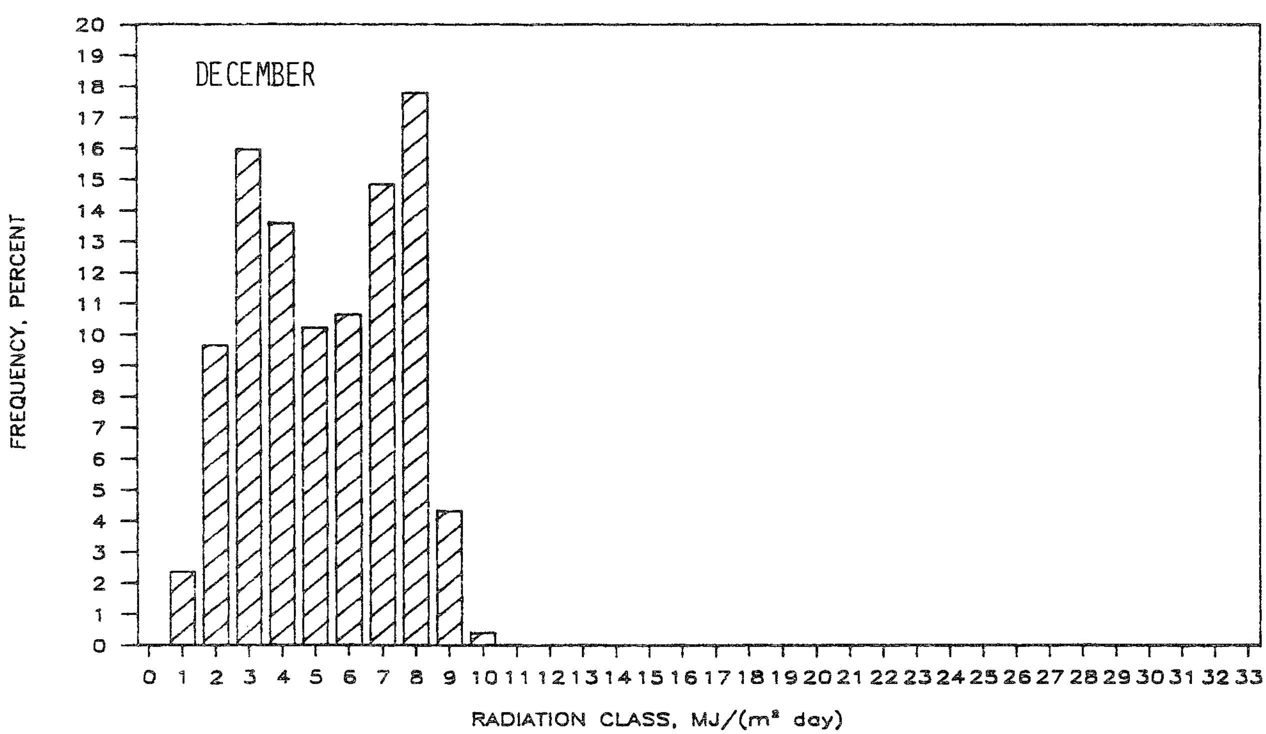

Figure 6. Frequency distribution of daily total solar radiation for December, St. Paul, 1963-1985.

An analysis of the weather associated with the 713 December days between 1963-1985 showed the following:

a. Days with 0.04-4.19 MJ/(m^2 day)[1-100 cal/(cm^2 day)] radiation are typically overcast, only 2 days had less than 8/10 cloud cover, and over 65% had no sunshine recorded. These days are also relatively warm with 63 percent of the days exceeding 30°F.

b. Days with greater than 5.23 MJ/(m^2 day)[125 cal/(cm^2 day)] radiation were essentially free of clouds (34 percent) and about half had more than 80 percent sunshine. These clear days are also colder with the maximum temperature less than 30°F (65 percent).

c. Days with 4.23-5.23 MJ/(m^2 day)[101-125 cal/(cm^2 day)] are transition days between the two populations.

The relationship between cloud cover and sunshine is an inverse one; when one is high the other is low. The sunshine measurement, while related to solar radiation, is separate and quite different. It is usually expressed as the percent of possible sunshine while cloud cover is expressed in tenths. This relationship between the percent of possible sunshine and the amount of cloud cover as measured at the Minneapolis-St. Paul WSO AP is depicted in Figure 8.

An interesting and unusual illustration of how the mean daily radiation on a weekly basis varies in the course of a year with a given amount of cloud cover is provided in Figure 9. Within each cloud cover category a similar annual curve is shown. This, of course, results from the annual fluctuation of solar radiation. Of particular interest is the fact that for the 1/10, 2/10, and 3/10 cloud cover categories there is no appreciable change in the maximum radiation. It is of interest, too, that both the maximum and minimum decrease, with the maximum showing the greater change. And since the maximum decreases more, the range decreases as well.

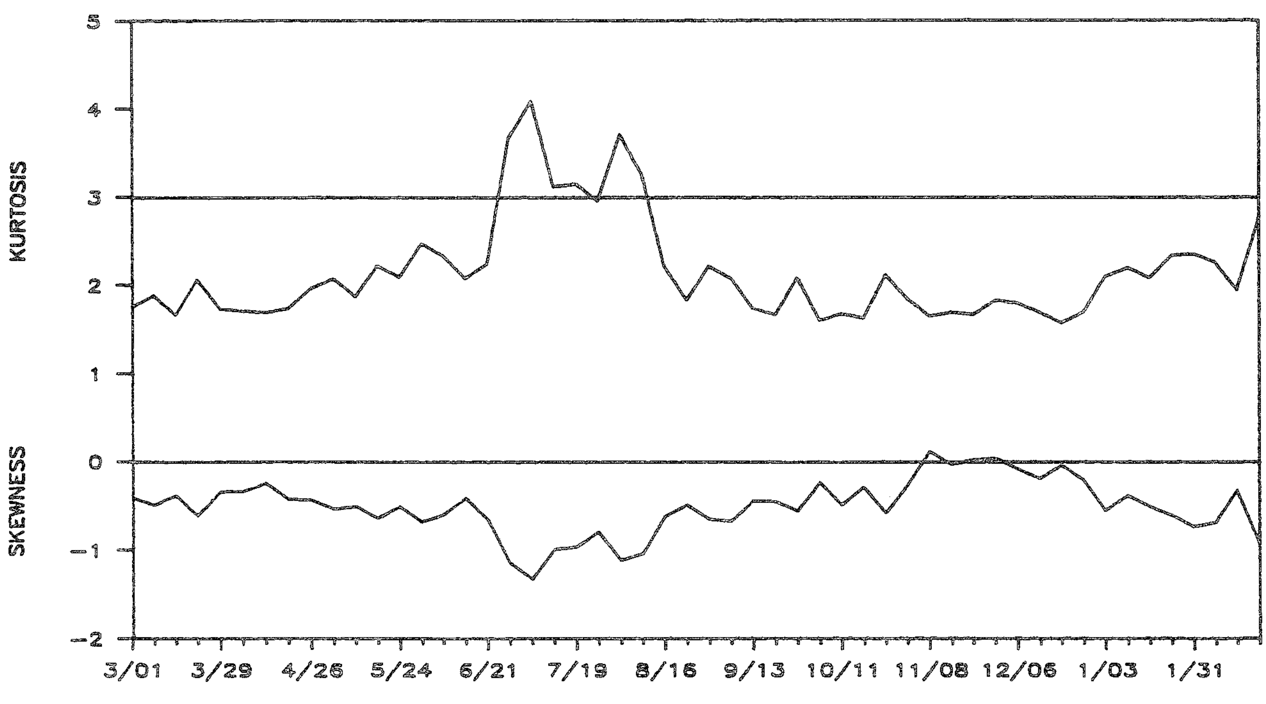

Figure 7. Mean weekly values of kurtosis and skewness. A normal frequency distribution has a value of 3 for kurtosis and 0 for skewness.

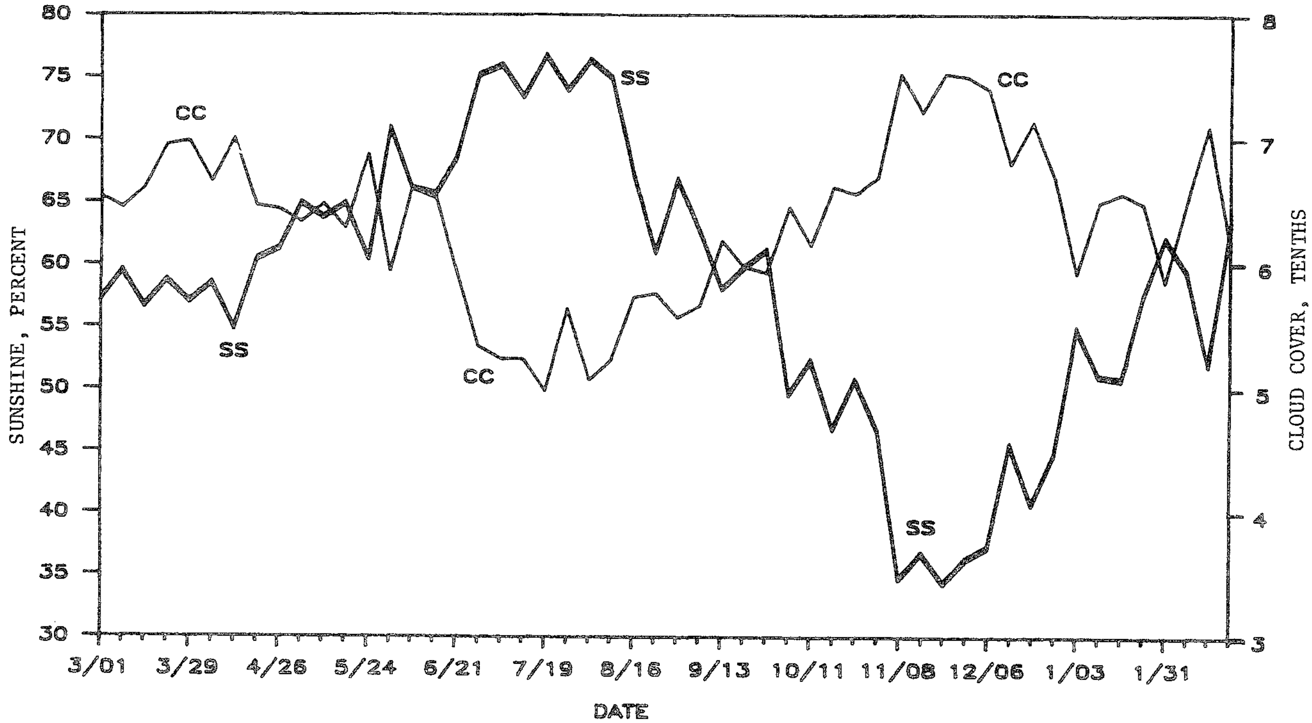

Figure 8. Mean weekly values of sunshine in percent of possible (SS; left scale) and cloud cover in tenths (CC; right scale) at Minneapolis-St. Paul WSO AP, 1963-1985.

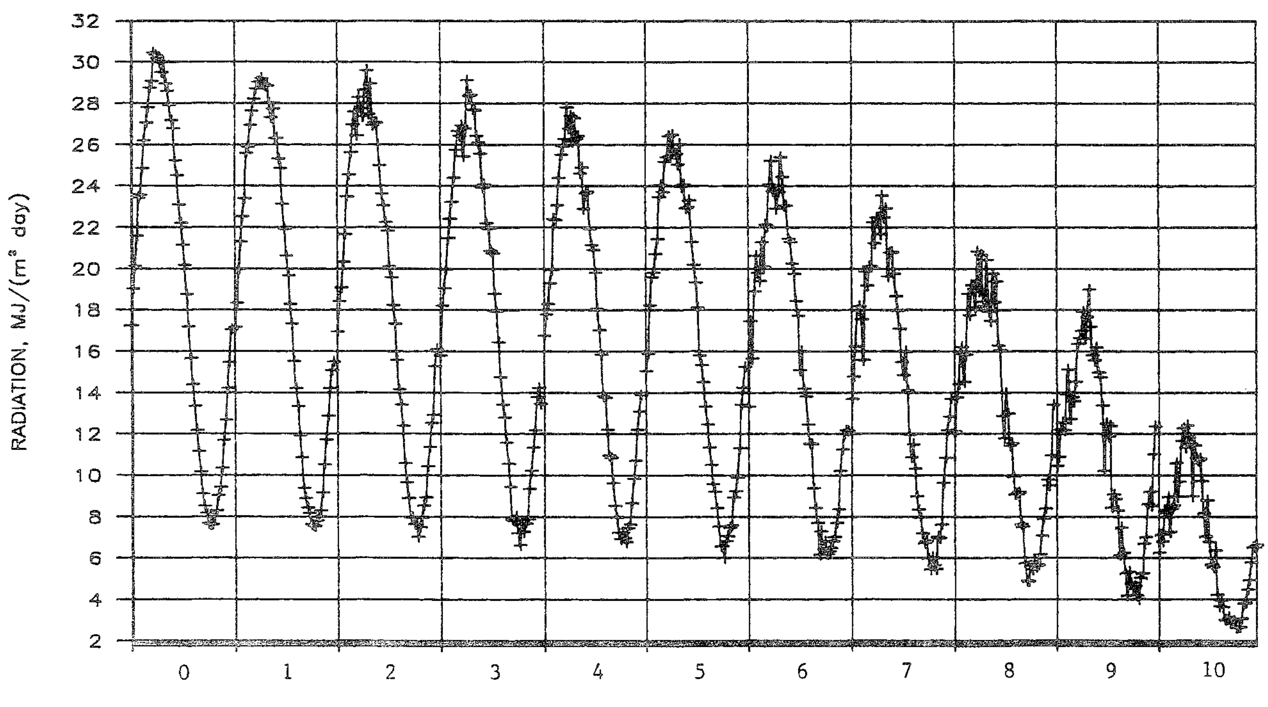

Figure 9. The variation in daily total solar radiation by week within each cloud cover category (0 equals clear and 10 equals 10/10 or overcast).

It is evident from Table 5 that the maximum cloud cover is to be found in November and December. At that time 8/10 and greater cloud cover occurrence ranges between 62-63 percent, and the lower amounts of cloud cover have their minimum occurrence. The lowest amount of cloud, up to 3/10 cover, is a common summer feature, with maximum occurrence in July, August, and September. The intermediate cloud cover amounts, 4/10 to 7/10, double between the minimum in November and December to the maximum in July. The latter occurrence is essentially a feature of the typical summer daytime heating and the development of cumulus clouds. It becomes particularly evident when the frequency of cloud cover on an hourly basis is considered, since cumulus clouds are almost always features of daytime heating. They typically form by late forenoon only to dissipate with the setting of the sun.

Table 5. Cloud cover occurrence in percent at the Minneapolis-St. Paul WSO AP. (National Climatic Data Center, 1963-1985).

	Cloud Cover Categories (0-10)[1]		
Month	0/10 to 3/10	4/10 to 7/10	8/10 to 10/10
January	27%	24%	49%
February	26	23	51
March	24	23	53
April	22	24	54
May	22	30	48
June	24	33	43
July	31	41	28
August	31	36	33
September	31	28	41
October	26	24	50
November	17	21	62
December	20	17	63
Annual	25	27	48

[1]0 represents clear skies and 10 represents complete cloud cover (overcast).

Atmospheric Transmissivity

The amount of radiation received at the outer limits of the earth's atmosphere at 45°N is shown in Figure 3. It varies from a maximum of 42.82 MJ/(m^2 day)[1023 cal/(cm^2 day)] on June 21 to a low of 10.67 MJ/(m^2 day)[255 cal/(cm^2 day)] on December 21. These are calculated values based on an assumed solar constant of 1395.2 W/m^2 [2.0 cal/(cm^2 min)]. The equation for the extraterrestrial radiation (Y) received at 45°N is:

[Equation 1]

$$Y = [27.70 + 14.98(A) - 5.81(B) + 0.41(C) + 0.26(D)]\ \mathrm{MJ/(m^2\ day)}.$$

The standard error of Y estimate is 0.02 MJ/(m^2 day) and r^2 is 0.99.

$A = \sin(DN)\ (2\pi/365)$
$B = \cos(DN)\ (2\pi/365)$
$C = \sin(2DN)\ (2\pi/365)$
$D = \cos(2DN)\ (2\pi/365)$
DN = Day number;
DN is 1 on March 1 and 365 on February 28.

On passing through an atmosphere free of clouds, a reduction in solar radiation at St. Paul occurs amounting to an annual average of about 28 percent, Figure 10, and Table 6, column 8. Two factors are responsible for this clear-day radiation reduction. One is the angular path of solar rays at our latitude, since the sun is overhead only between 23.5°N and 23.5°S latitude. The other is the turbidity of the atmosphere. An important element in atmospheric turbidity is the moisture content of the atmosphere. Characteristically a minimum amount of vapor is found in the winter and a maximum in the summer. The annual variation in the clear-day atmospheric transmissivity is readily apparent in Figure 10, and it reflects the seasonal water vapor differences. The extension of low transmissivity into September, October, and early November is probably due to atmospheric dust content resulting from the generally lower atmospheric circulation in summer and early autumn. In the absence of clouds the atmosphere is generally most transparent in February, in spite of the long path through the atmosphere. One reason is the low vapor content. Another reason for the greater February transmissivity is the snow cover over much of the region which reduces the opportunity for dust to enter the atmosphere.

The average daily transmissivity under all conditions, also in Figure 10, and Table 7, column 4, is not only lower, but it exhibits much greater variation during the course of the year than does the clear-day transmission. Two identifiable low values occur, and both are associated with the greater cloud cover at that time. One is in April and the other in November. Both are associated with the proximity of the polar front. A summer maximum in July is apparent as well as the winter maximum in February, due in both cases to the lower frequency of clouds. On an annual basis under all conditions, only about 49 percent of the possible amount of radiation reaches the earth's surface at St. Paul.

Table 6. Mean clear-day values of total, direct beam, and diffuse radiation, MJ/(m^2 day), atmospheric transmissivity, percent, and ratio of diffuse to total radiation, percent. Total radiation values are for 1963-1985. Direct beam and diffuse values are for September 1, 1977 - December 31, 1985.

FIRST DATE	EXT RAD	TOTAL CC=0	N	TOTAL SS=100	N	TOTAL CC= 0 SS=100	TRANS CC= 0 SS=100	N	DIRECT CC= 0 SS=100	DIFFUSE CC= 0 SS=100	DIFFUSE RATIO CC= 0 SS=100	DIRECT & DIFFUSE N
3/01	22.77	17.29	13	17.16	20	17.41	76.5	11	14.49	3.02	17.3	6
08	24.73	19.05	17	18.46	20	18.96	77.3	11	14.98	3.38	18.4	5
15	26.71	20.13	16	19.84	21	20.09	75.5	12	16.92	2.76	14.0	6
22	28.67	21.64	8	21.43	9	21.98	76.8	5	19.17	3.31	14.7	1
29	30.58	23.44	9	23.19	14	23.65	77.0	8	20.09	3.68	15.5	1
4/05	32.42	23.61	16	23.52	19	23.78	73.7	12	19.97	3.68	15.6	1
12	34.17	24.91	9	25.32	7	24.78	72.2	4	20.58	4.07	16.5	3
19	35.79	26.25	9	25.87	18	26.25	72.6	9	21.50	4.64	17.7	5
26	37.29	27.08	10	27.21	12	27.46	73.1	6	23.89	4.14	14.8	3
5/03	38.63	27.84	8	27.96	17	28.30	73.3	6	25.62	3.18	11.0	1
10	39.80	28.80	9	28.30	12	28.55	71.6	6	24.34	4.56	16.0	*
17	40.79	29.09	8	28.92	17	29.09	71.5	8	23.96	5.02	17.3	6
24	41.61	30.47	7	29.76	11	30.51	73.4	5	24.36	6.20	20.3	1
31	42.21	30.35	9	30.18	12	30.43	72.0	5	26.25	4.14	13.6	1
6/07	42.61	30.18	7	30.01	8	30.43	71.4	5	24.65	5.82	19.1	2
14	42.80	29.97	3	29.05	6	30.64	71.5	2	26.24	4.65	15.2	*
21	42.78	29.51	11	29.47	14	29.18	68.2	6	26.19	4.61	15.8	*
28	42.56	30.05	8	29.51	12	29.51	69.3	5	25.78	4.14	13.8	1
7/05	42.10	28.97	5	29.22	7	29.43	69.9	3	22.35	5.82	15.7	1
12	41.48	28.59	6	27.96	8	28.67	69.1	4	24.70	4.25	13.3	2
19	40.64	27.92	10	27.88	15	28.30	69.7	7	23.77	3.81	14.3	4
26	39.65	27.17	6	26.83	7	27.29	68.8	4	23.98	4.35	13.7	1
8/02	38.47	26.79	8	26.20	7	27.04	70.4	4	21.93	4.27	15.1	1
09	37.15	25.24	9	25.87	12	26.37	70.9	5	22.31	4.10	16.0	2
16	35.68	24.53	5	24.36	12	24.61	67.9	2	21.04	3.65	14.8	*
23	34.09	23.11	20	23.61	10	23.61	69.4	9	19.94	3.49	19.4	*
30	32.40	22.23	12	21.93	8	22.06	68.6	5	18.97	2.98	15.7	3
9/06	30.60	21.14	19	21.14	14	21.43	70.3	10	17.81	3.31	19.5	2
13	28.76	20.22	14	20.30	14	20.30	70.6	9	17.25	2.65	16.7	6
20	26.86	18.75	13	18.17	19	18.63	70.0	10	16.00	2.68	18.3	4
27	24.95	17.20	22	17.04	30	17.29	69.5	17	15.57	2.47	20.6	2
10/04	23.05	15.66	16	15.74	17	15.82	69.1	14	13.19	2.34	31.9	3
11	21.19	14.40	15	14.52	16	14.44	67.8	11	12.77	2.43	30.4	1
18	19.38	13.35	10	13.31	17	13.39	68.9	7	10.63	2.22	29.0	*
25	17.68	12.18	9	12.06	12	12.14	67.6	7	9.15	2.20	28.8	2
11/01	16.10	11.18	14	11.13	12	11.26	69.9	7	8.96	1.67	15.7	1
08	14.69	10.17	9	10.38	8	10.42	69.9	5	7.79	1.88	19.5	1
15	13.45	9.13	13	9.13	13	9.17	68.1	9	7.45	1.57	16.7	2
22	12.44	8.54	10	8.66	6	8.66	69.3	6	6.91	1.55	18.3	1
29	11.62	8.16	7	8.12	8	8.25	70.5	5	6.63	1.72	20.6	3
12/06	11.06	7.66	7	7.70	8	7.74	69.9	6	5.09	2.39	31.9	2
13	10.74	7.62	18	7.74	11	7.79	72.5	9	5.64	2.46	30.4	4
20	10.68	7.66	14	7.66	12	7.62	71.4	7	5.41	2.19	28.8	3
27	10.87	8.04	20	7.91	19	8.04	74.0	15	5.94	2.09	26.2	4
1/03	11.34	8.41	18	8.37	21	8.54	74.9	13	6.64	1.91	22.2	3
10	12.04	9.13	15	9.08	17	9.21	74.5	12	6.73	2.34	25.8	4
17	12.98	9.46	15	9.38	12	9.42	73.1	8	6.14	2.64	28.6	3
24	14.14	10.38	16	10.46	18	10.38	73.6	15	7.58	2.26	23.0	4
31	15.53	11.72	25	11.72	26	11.93	76.1	17	9.67	2.46	20.3	4
2/07	17.07	12.68	15	12.60	14	12.68	74.6	9	10.19	2.85	21.8	2
14	18.75	14.27	14	14.23	17	14.06	76.2	8	11.26	2.60	18.7	1
21	20.59	15.49	17	15.45	18	15.49	76.5	12	12.42	3.00	19.4	*

* = Estimated from equations 3 and 4 as there were no clear days. N = Number of clear-day values.
CC = 0 means the Cloud Cover as 0/10 and SS = 100 means the Sunshine was 100 percent of possible.

Clear-Day Total Radiation

Because the presence of clouds is not always apparent from the radiation trace of the recorders, especially in the case of high, thin cirrus, two different observations were used to define a clear-day. One was from the sunshine recorder that provides a continuous record, and the other was the hourly cloud-cover observation taken by an observer. In Figure 11 and Table 6 it is indicated that there is little difference whether a clear-day is defined as: one in which the cloud-cover observation indicated no clouds were present, Table 6, column 3; when the sunshine measurement records 100 percent sunshine, Table 6, column 5; or when both occur on the same day, Table 6, column 7. However, if the maximum measured daily radiation values are plotted, as in Figure 11, it is apparent that they exceed the defined clear-day values throughout the year. In June the difference is approximately 8 percent greater and in December it is about 10 percent in excess.

There are probably two reasons why the maximum daily values exceeded the defined clear-day values. One is that the comparison was between individual days of unusual clarity and the average of clear days. The other is that the maximum value resulted from a radiation beam increased by reflection from the edges of the clouds present, none of which interrupted the direct solar beam. As a result the radiation trace indicated no clouds. Whether the maximum value day is actually entirely cloudless is not all that important. What is important is that the maximum values obtained do not differ substantially from the defined clear-day values. More importantly perhaps, is that these values approximate the upper limit to solar radiation that can be expected at this station.

When both the cloud cover observation and sunshine measurement indicated a particular day as being clear, the radiation for that day was counted and is shown in Figure 12. The curve which best fits the data is also depicted. The equation for that curve is:

[Equation 2]

$$Y = [19.54 + 10.90(A) - 3.41(B)]\ MJ/(m^2\ day).$$

Standard error of Y estimate = $0.91\ MJ/(m^2\ day)$ and r^2 is 0.98.
Y = the estimated daily radiation total.
A and B are defined as noted in Equation 1.

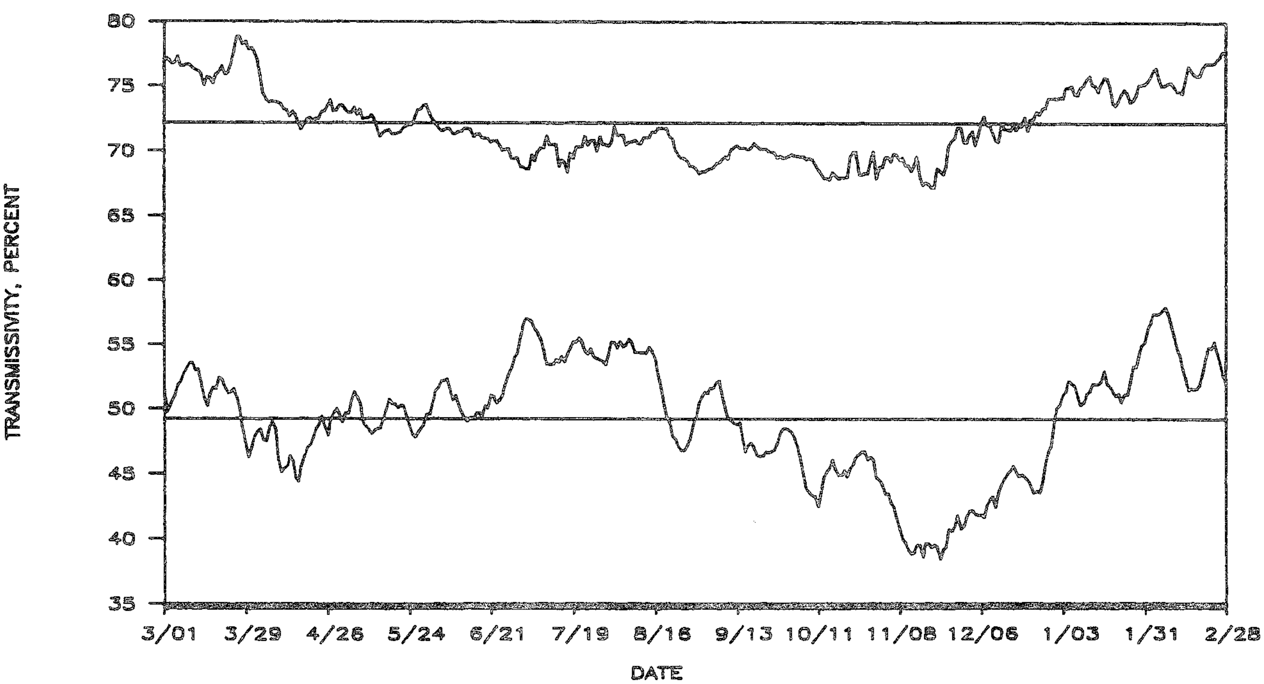

Figure 10. Mean daily transmissivity in percent of possible for clear-days (top) and all-days (bottom), St. Paul, 1963-1985.

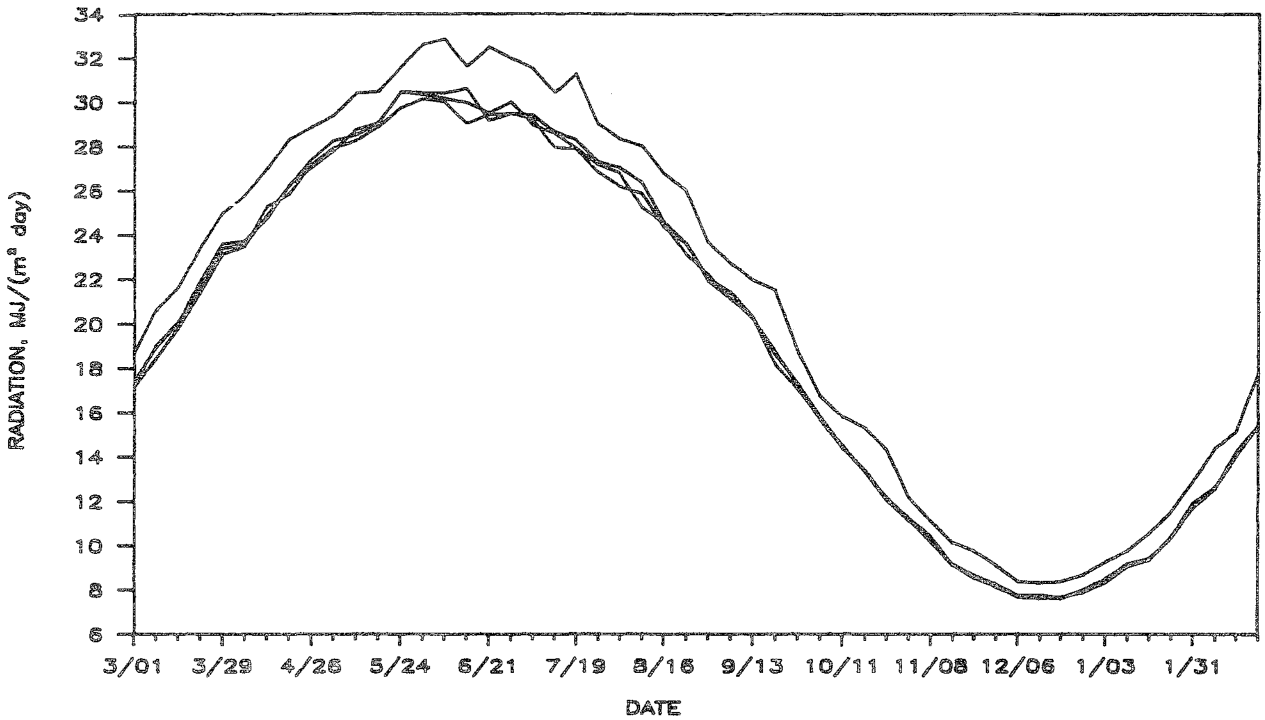

Figure 11. Comparison of clear-day definition methods of mean daily total radiation for each week. The top curve is the maximum value recorded. The other curves are for (1) 0 tenths cloud cover days, (2) 100 percent sunshine days, and (3) when both (1) and (2) occurred on the same day, 1963-1985.

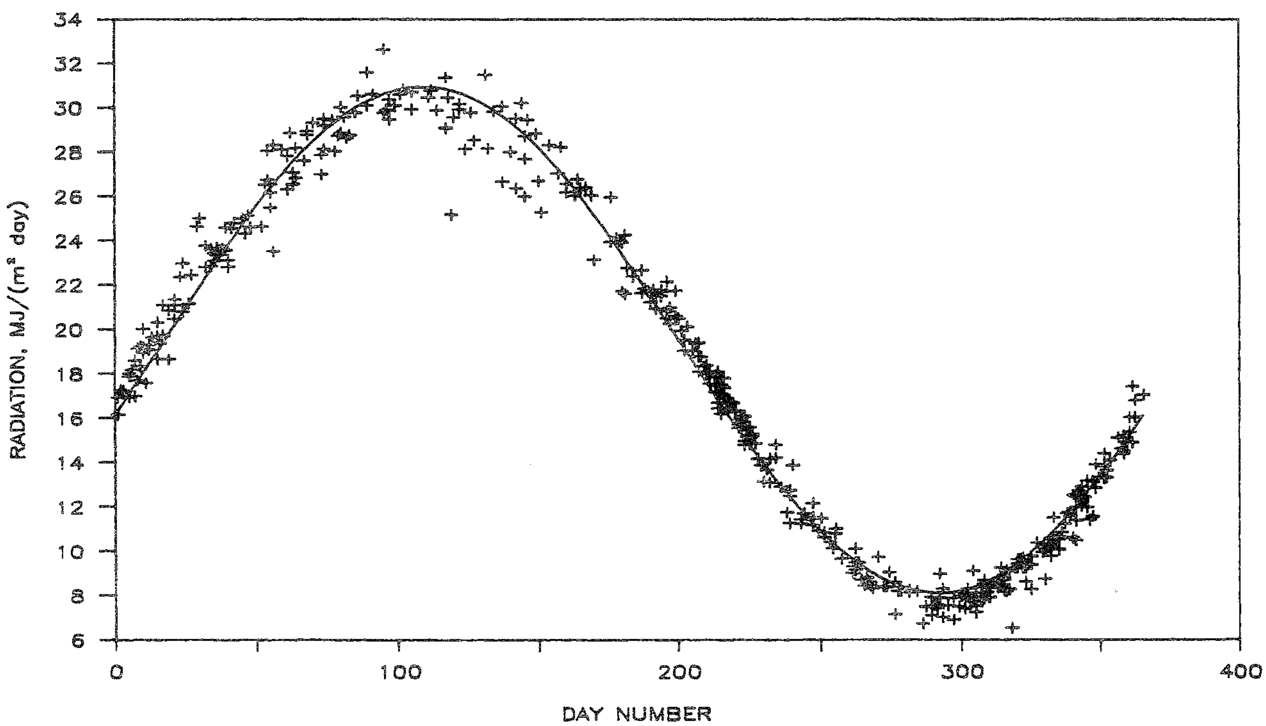

Figure 12. Clear-day total solar radiation values and the best-fit line of the values, St. Paul, 1963-1985. A clear-day is defined as one with 0 tenths cloud cover and 100 percent sunshine. March 1 = Day 1, June 8 = Day 100, September 16 = Day 200, and December 25 = Day 300.

Table 7. Mean extraterrestrial radiation and total solar radiation, MJ/(m^2 day), atmospheric transmissivity, percent, direct and diffuse radiation, MJ/(m^2 day), and percent diffuse radiation at St. Paul, and mean cloud cover, tenths, and sunshine, percent, Minneapolis-St. Paul WSO AP, 1963-1985.

FIRST DATE	EXT. RAD.	TOTAL RAD.	TRANS	CLOUD COVER	SUN-SHINE	DIRECT	DIFFUSE	DIFFUSE RATIO	N *	MAXIMUM DIFFUSE	MINIMUM DIFFUSE	MEDIAN DIFFUSE	STD DEV DIFFUSE
3/01	22.77	11.45	50.2	6.6	57.0	6.91	4.74	53.7	56	9.13	1.76	3.89	2.10
08	24.73	13.15	53.2	6.5	59.4	8.45	5.40	47.8	56	10.55	2.01	4.98	2.04
15	26.71	13.40	50.2	6.6	56.5	8.60	4.99	52.0	55	10.13	2.22	5.15	1.98
22	28.67	14.75	51.5	7.0	58.6	8.99	5.70	50.0	56	10.38	1.59	5.99	2.15
29	30.58	14.64	47.9	7.0	56.9	8.13	6.04	54.8	56	11.01	1.93	6.32	2.21
4/05	32.42	15.79	48.7	6.7	58.4	7.97	6.39	56.2	56	12.26	1.97	6.45	2.16
12	34.17	15.19	44.4	7.0	54.7	10.95	5.63	47.1	56	10.84	2.05	4.98	2.30
19	35.79	17.23	48.1	6.5	60.3	12.14	6.10	43.8	56	10.76	2.13	6.15	2.22
26	37.29	18.00	48.3	6.4	61.2	13.00	6.80	42.7	53	11.13	3.39	6.61	2.12
5/03	38.63	19.79	51.3	6.3	64.8	12.17	7.29	45.7	56	11.22	2.72	7.58	2.03
10	39.80	19.06	47.9	6.5	63.6	12.56	7.19	44.8	49	12.93	3.93	6.78	2.52
17	40.79	20.54	50.4	6.3	64.8	14.33	7.07	42.4	50	11.93	2.72	6.95	2.24
24	41.61	20.15	48.4	6.9	60.3	11.08	8.27	50.7	52	13.48	4.06	8.04	2.39
31	42.21	22.04	52.2	5.9	70.7	13.47	8.00	42.2	53	12.26	3.81	8.08	2.04
6/07	42.61	21.43	50.3	6.6	65.9	13.05	7.76	44.1	45	11.85	4.44	7.49	1.84
14	42.80	20.97	49.0	6.6	65.3	11.23	8.06	47.5	47	12.22	3.60	7.87	2.29
21	42.78	21.74	50.8	6.0	68.4	14.28	7.35	41.3	55	11.93	3.10	7.24	2.25
28	42.56	23.80	55.9	5.3	75.1	15.19	7.38	39.1	56	12.47	3.47	7.74	2.28
7/05	42.10	23.52	55.9	5.2	75.9	16.46	7.62	35.5	56	12.14	4.10	7.62	2.15
12	41.48	22.11	53.3	5.2	73.3	14.20	7.42	39.3	55	12.35	4.10	7.49	2.02
19	40.64	22.71	55.9	5.0	76.6	13.94	7.33	39.4	56	12.93	2.89	7.62	2.19
26	39.65	20.84	52.6	5.7	73.8	12.99	7.70	41.3	56	11.22	4.35	7.49	1.99
8/02	38.47	21.38	55.6	5.1	76.2	13.66	7.18	38.1	51	11.26	3.10	7.12	2.16
09	37.15	20.27	54.6	5.2	74.8	13.11	6.64	38.9	56	11.39	3.39	6.53	2.02
16	35.68	18.13	50.8	5.7	67.0	11.04	6.25	43.8	56	11.26	2.30	6.15	2.16
23	34.09	16.20	47.6	5.8	60.8	8.06	5.67	51.9	56	8.83	2.76	5.53	1.68
30	32.40	16.63	51.4	5.6	66.7	11.26	5.24	39.1	55	8.58	2.55	5.19	1.65
9/06	30.60	15.22	49.7	5.7	62.4	9.97	5.28	43.0	56	9.04	1.63	5.19	1.64
13	28.76	13.67	47.5	6.2	57.9	8.97	4.76	45.4	56	7.87	1.13	4.48	1.76
20	26.86	12.50	46.5	6.0	59.6	8.77	4.32	43.5	56	7.70	1.76	4.02	1.48
27	24.95	12.18	48.9	5.9	61.1	7.17	4.51	48.4	56	7.53	1.80	4.65	1.50
10/04	23.05	9.98	43.3	6.5	49.4	4.95	4.16	58.5	56	6.45	1.51	3.93	1.42
11	21.19	9.72	45.9	6.2	52.2	5.20	3.68	56.6	51	6.32	1.51	3.60	1.34
18	19.38	8.53	44.0	6.6	46.6	4.00	3.27	60.5	51	6.03	1.00	3.06	1.25
25	17.68	8.31	46.9	6.6	50.6	5.98	2.96	42.7	51	5.53	0.84	2.55	1.28
11/01	16.10	7.12	44.3	6.7	46.5	4.65	3.11	51.5	56	5.06	1.05	3.26	1.18
08	14.69	5.58	38.0	7.5	34.6	2.69	2.84	68.9	54	5.19	0.84	2.93	1.11
15	13.45	5.35	39.7	7.2	36.7	3.06	2.81	62.7	52	5.48	0.29	2.80	1.21
22	12.44	4.95	39.8	7.5	34.2	2.01	2.94	71.3	56	4.98	0.96	2.85	1.10
29	11.62	4.82	41.4	7.5	36.1	2.21	2.77	70.5	56	4.77	0.63	2.76	0.96
12/06	11.06	4.78	43.2	7.4	37.2	2.34	2.73	63.5	53	3.98	1.34	2.72	0.75
13	10.74	4.87	45.4	6.8	45.5	2.74	2.42	58.0	49	4.14	0.80	2.34	0.82
20	10.68	4.71	44.1	7.1	40.5	2.22	2.54	64.5	49	3.93	0.63	2.51	0.80
27	10.87	5.10	46.9	6.7	44.6	2.29	2.63	65.1	51	4.73	0.84	2.51	0.89
1/03	11.34	5.93	52.3	5.9	54.8	2.98	2.88	58.6	49	4.56	0.84	3.01	0.96
10	12.04	6.18	51.3	6.5	50.9	2.81	3.18	63.4	49	4.98	0.96	3.26	0.92
17	12.98	6.69	51.5	6.6	50.7	3.69	3.38	55.0	51	6.11	1.47	3.10	1.23
24	14.14	7.51	53.0	6.5	57.4	3.72	3.84	59.1	56	6.03	1.63	4.06	1.31
31	15.53	8.83	56.8	5.9	62.0	5.18	4.10	51.8	53	7.24	1.84	4.10	1.41
2/07	17.07	9.52	55.8	6.5	59.3	4.98	4.38	57.2	53	7.20	1.97	4.14	1.40
14	18.75	9.64	51.4	7.1	51.8	4.62	4.59	62.3	53	7.79	2.13	4.73	1.53
21	20.59	11.41	55.4	6.1	63.1	5.93	4.40	54.6	55	8.50	1.13	4.35	1.80

* N is for the direct and diffuse data. All other parameters are based on 161 values per week.

Clear-Day Direct Beam and Diffuse Radiation

Total radiation in any clear period has two parts: direct beam radiation and diffuse radiation. The latter is that portion of the solar beam which has been scattered and reflected by various atmospheric constituents on its way through the atmosphere. The amount of scattering varies with the turbidity of the atmosphere and with the path length of the solar beam through the atmosphere. The length of the solar beam is a function of both the season and the time of day. The turbidity is greatly affected by particles such as dust and pollutants, and by the water vapor content. The mean clear-day direct beam and diffuse radiation for each climatological week is shown in Table 6 and Figure 13. The equation which best fits the clear-day direct beam radiation (Y) curve in Figure 13 is:

[Equation 3]

$Y = [0.68 + 0.39(A) - 0.16(B)]\ MJ/(m^2\ day)$.
Standard error of Y estimate = $0.05\ MJ/(m^2 day)$ and r^2 is 0.97.
$A = \sin$ (week number) $(2\pi/52)$
$B = \cos$ (week number) $(2\pi/52)$

The equation which best fits the clear-day diffuse radiation (Y) curve shown in Figure 13 is:

[Equation 4]

$Y = [0.14 + 0.06(A) - 0.01(B)]\ MJ/(m^2\ day)$.
Standard error of Y estimate = $0.03\ MJ/(m^2\ day)$ and r^2 is 0.67.
A and B are defined as noted in Equation 3.

During clear-days, diffuse radiation averages about 19 percent of the total solar radiation for a majority of the year, (Table 6, column 12). A few exceptional cases have been observed in which the diffuse amounted to only 11 to 14 percent of the total solar radiation received at the surface of the earth. Such days follow, by about one day, the passage of a cold front bringing fresh, dry, continental Polar air. They typically have deep blue skies and cool temperatures (the lower the temperature the drier the air). The ratio of diffuse to total solar radiation under clear-day conditions varies some during the course of the year, ranging from a high of 25 to 30 percent in December and January to a minimum of 15 to 20 percent in early April and May (Table 6, column 12).

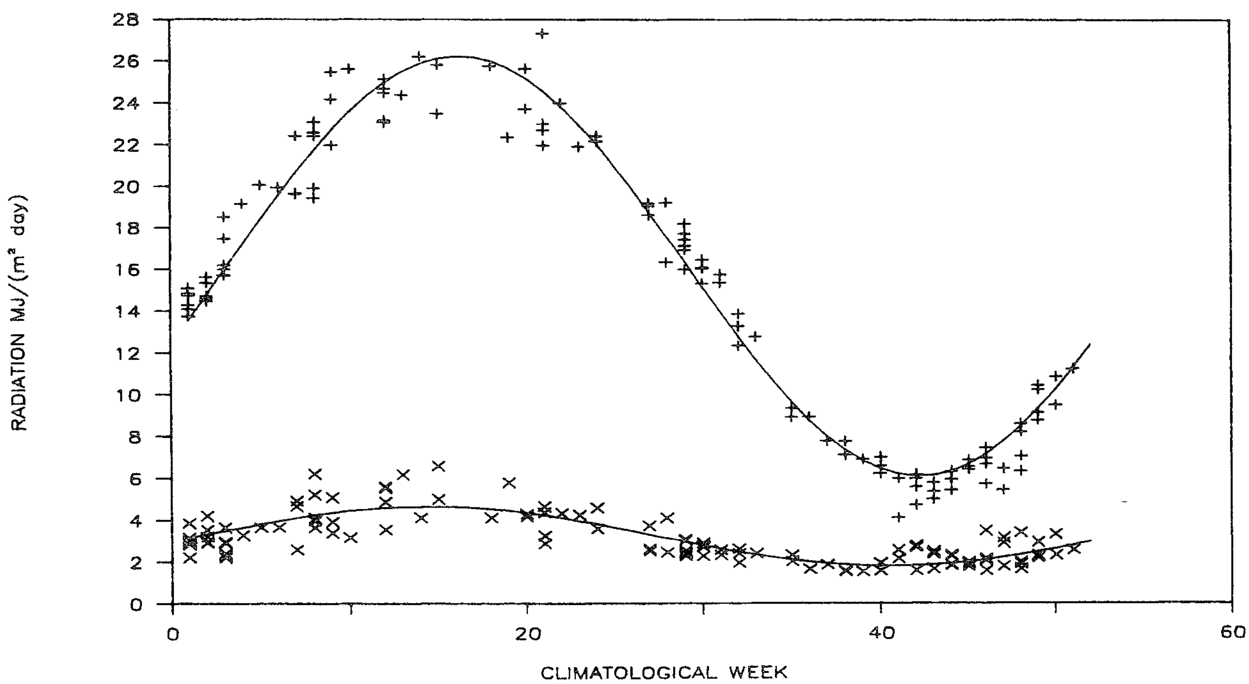

Figure 13. Clear-day total direct beam solar radiation (top) and clear-day diffuse radiation (bottom) values and the best-fit line of those values, St. Paul, September 1,1977-December 31, 1985. A clear-day is defined as one with 0 tenths cloud cover and 100 percent sunshine. March 1-7 = Week 1, July 12-18 = Week 20, November 29-December 5 = Week 40.

Clear Solar-Noon Radiation

The amount of radiation received at solar noon during days which had clear periods at noon, though the entire day was not necessarily clear, has been noted in the microclimate station record for a number of years. The frequency that clear-noon periods were observed in the 1963-1985 period is shown in Figure 14. There are two peak periods, with late August to mid-October the major one, and mid-February the minor one. The minimum occurrences are centered around mid-June, St. Paul's peak precipitation period, and in mid-November to mid-December. The solar noon measured values and the curve that best fits the data are shown in Figure 15. The equation for the clear-noon value (Y) is:

[Equation 5]

$Y = [716.78 + 264.06(A) - 71.99(B)]$ W/m^2.
Standard error of Y estimate = 40.40 W/m^2 and r^2 is 0.95.
A and B are defined as noted in Equation 1.

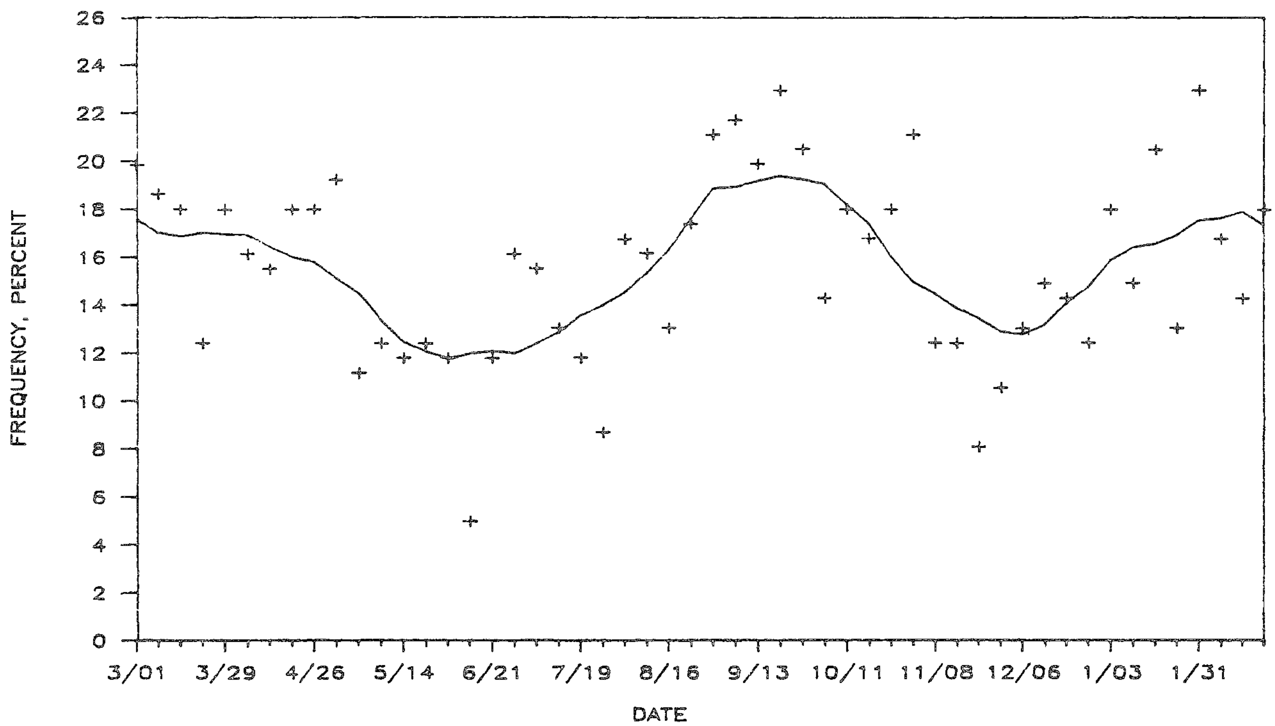

Figure 14. Weekly frequency of occurrence of clear solar-noon periods for each climatological week, St. Paul, 1963-1985. The line is a 9-week running mean.

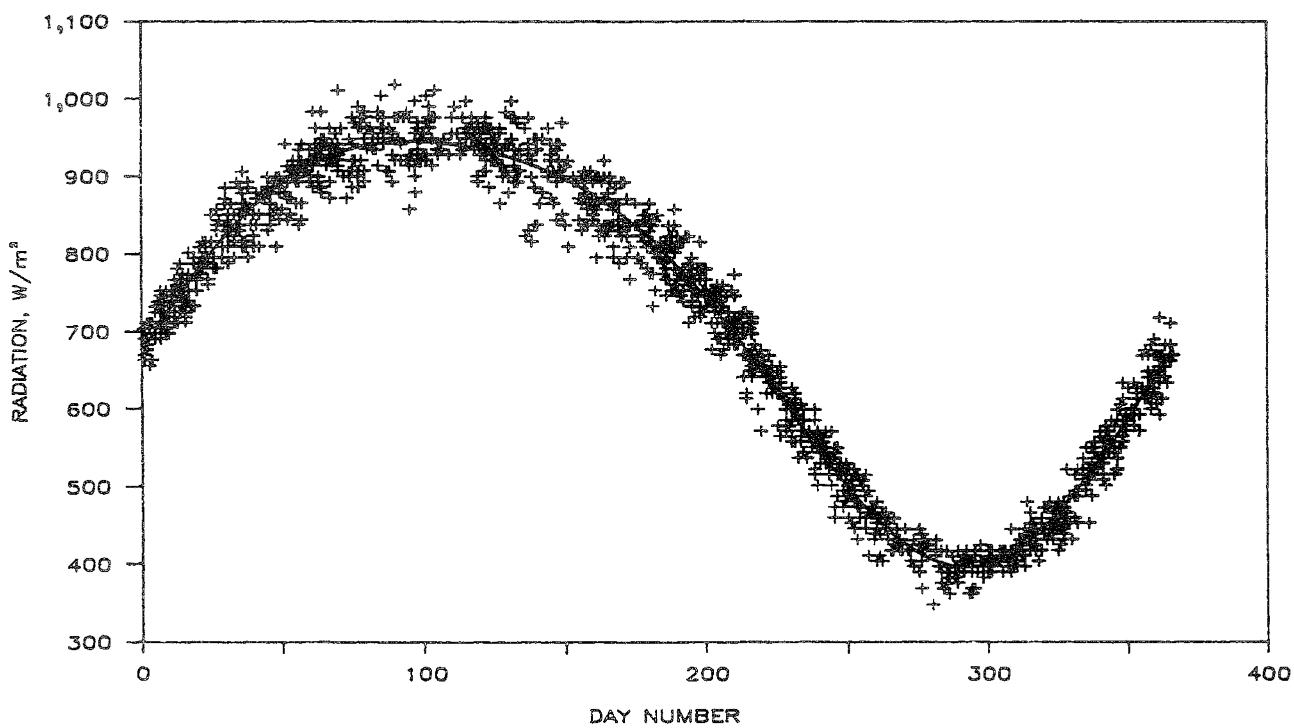

Figure 15. Clear-noon period total solar radiation (direct beam plus diffuse) and the best-fit line of the daily values, St. Paul, 1963-1985.

Average-Day Total Radiation

In Table 7 are listed the mean daily total radiation, cloud cover, and sunshine conditions for each week of the year. The period June 28 to August 15, when sunshine averages more than 70 percent, is the "bright" time of the year. In contrast, the "gloomy" part of the year is November 8 through December 12, if less than 40 percent of possible sunshine is used as the criterion for gloomy.

Mean solar radiation for selected cloud cover amounts is shown in Figure 16 and the mean for all conditions in Figure 17.

The equation for the average daily radiation (Y) that best fits the data shown in Figure 17 is:

[Equation 6]

$$Y = [13.61 + 8.11(A) - 3.01(B) - 0.72(C) + 0.60(D)] \text{ MJ/(m}^2 \text{ day)}.$$

The standard error of estimate is 1.21 MJ/(m^2 day), a relatively large value but not unexpected, since the daily radiation estimate is based on a wide range of conditions. The r^2 is 0.96. A, B, C, and D are defined as noted in Equation 1.

Average-Day Direct Beam and Diffuse Radiation

The two solar radiation components, the uninterrupted solar beam and radiation that has been scattered and reflected on its downward path, contain very similar wavelengths ranging from approximately 0.3-4 µm at the earth's surface. Because shorter wavelengths are scattered more than longer wavelengths, diffuse radiation is proportionately richer in the shorter wavelengths. That is, there is a higher percentage content of blue than red light in the diffuse radiation (Monteith, 1973). Diffuse radiation is generally pictured as being isotropic, coming from all directions equally from the sky hemisphere surrounding an object at the surface of the earth. For most considerations this is an acceptable estimation (Campbell, 1977). However, there is actually somewhat greater diffuse radiation in the direction of the sun and along the horizon than elsewhere in the sky.

In Table 7 are listed the mean diffuse and direct beam radiation values for each week. Also listed are the maximum, minimum, and median amounts of diffuse radiation, the standard deviation of the diffuse radiation and the ratio of the diffuse to the total radiation. From April 12 through October 3 the ratio is generally less than 50 percent with a minimum of 35 percent during July 5-11. This is a direct result of the lower amount of cloud cover and higher solar altitude. Maximum diffuse radiation occurs between November 8 and December 12. Much of the diffuse increase is due to the amount of cloud cover at this time. A second reason is the position of the earth relative to the sun resulting in the solar beam passing through the maximum amount of atmosphere. It must also be recognized that at this time of the year the amount of both the total and diffuse radiation is small. Thus any errors in the measured values, however slight, are greatly magnified.

Direct beam radiation, since it comes from a specific point or position in the sky, is amenable to geometric calculation. For example, direct beam radiation on a horizontal surface (Sh) equals the direct beam on a surface perpendicular to the solar rays (Sp) modified by the sine of the sun's elevation (α) above the horizontal surface. That is:

[Equation 7]

$$Sh = Sp \cdot \sin \alpha$$

Since the altitude of the sun for any time of day can be determined by calculation (Campbell, 1977) or estimated from graphs (List, 1958), this equation can be readily solved.

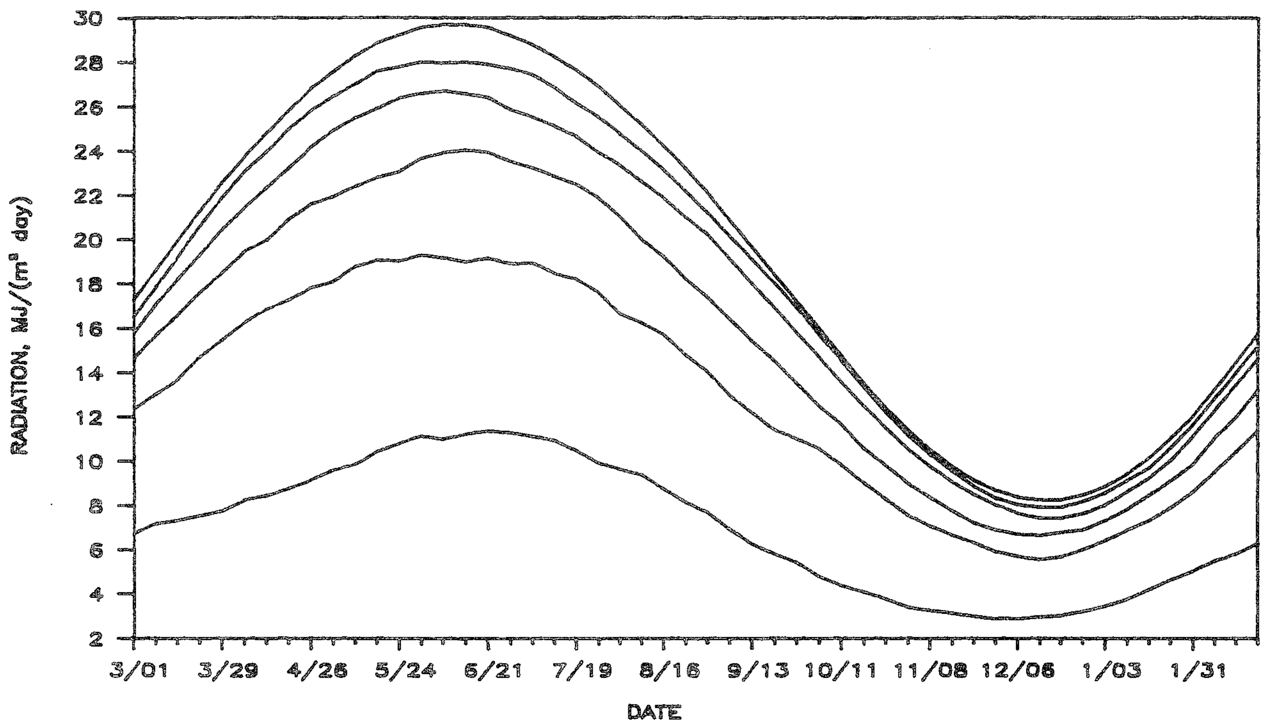

Figure 16. Mean daily total solar radiation received at St. Paul with (top to bottom) 0/10, 2/10, 4/10, 6/10, 8/10, and 10/10 cloud cover at the Minneapolis-St. Paul WSO AP, 1963-1985.

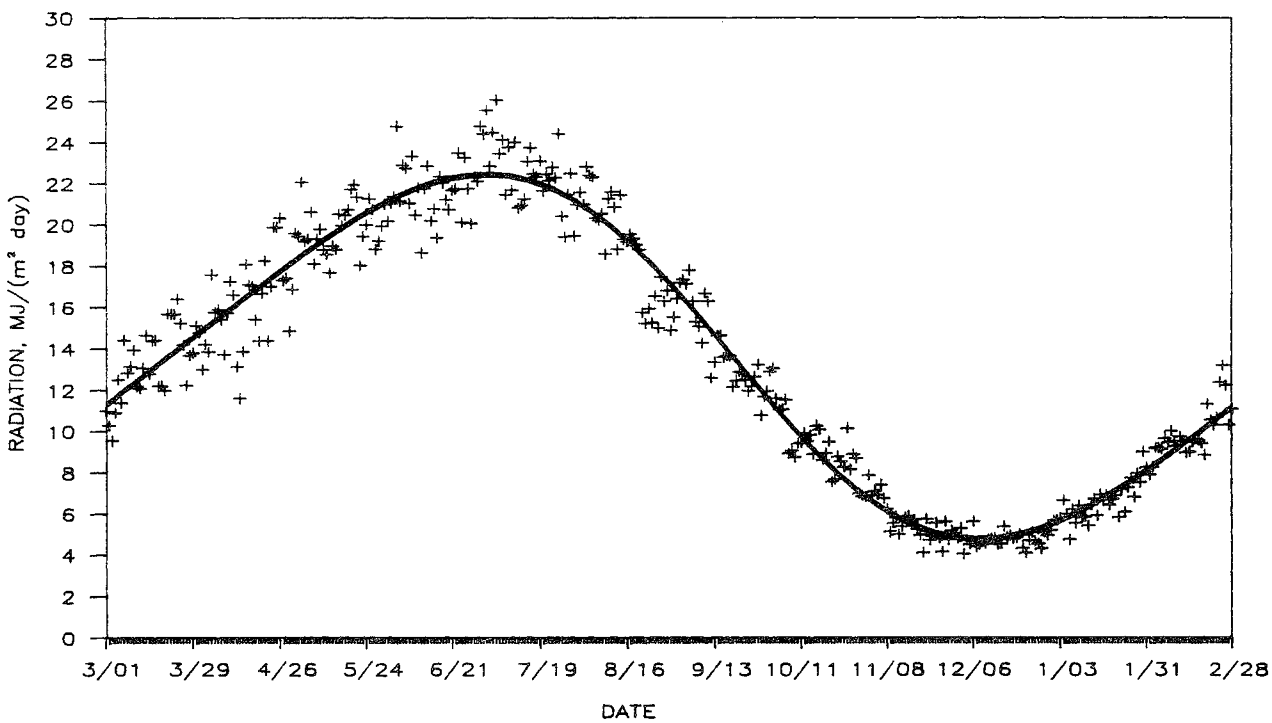

Figure 17. Mean daily total solar radiation values and the best-fit line of the values, St. Paul, 1979-1983.

Hourly Radiation

Determining the distribution of hourly values of measured radiation at St. Paul has necessarily been restricted to a limited time period. This is because of the difficulty in obtaining the hourly values with our recording system. Such values have to be read and recorded individually from each daily chart, since only daily total values are in computer files and available for analysis. Because of the labor involved, these within-day (hourly) values are limited to instantaneous values for each hour of the day for eight different weeks over the seven year period 1971-1977.

Results of this study of the hourly data are shown in Figures 18-37. The first part of the analysis is intended to give an overall picture of the distribution of the hourly values and also provide a general view of the daily course of the radiation. This is shown in Figures 18-25, where the mean, median and absolute maximum values are depicted. Because the illustrations are based only on instantaneous hourly values, the radiation curves are more regular than is natural.

Like the daily values, hourly measurements exhibit a negative skewness, with the median exceeding the mean during much of the year. The exception, again like the daily totals, is during the November and December period of low sun and high frequency of cloud cover. At this time the mean and median are essentially equal.

The radiation for both the local standard time (Central Standard Time, CST) and solar time (True Solar Time, TST) are shown in Figures 18-37. Since local time at St. Paul's longitude, 93°14'W, is ahead of the solar time during much of the year, in mid-February it is as great as 27 minutes, it is necessary to note this. This partly explains why the radiation values are sometimes noticeably offset from the local time scale.

Major differences in the hourly radiation values result from the cloud cover variations, and some seemingly curious results are apparent in each week to a greater or lesser degree. Perhaps the June 18-24 and August 2-8 examples in Figures 20-21 are the oddest. The peculiar configurations near mid-day are explained by the cloud cover. A longer record would probably smooth the variation somewhat. Nevertheless, what seems to be evident is the development and influence of clouds centered around the time of a high sun. That is, a high sun in terms of both season and time of day. Such a circumstance points toward a cloud forming process dependent upon solar heating, most probably convective type (cumulus) clouds. These clouds are almost wholly dependent upon solar heating.

The cumulative percent of radiation received for specific intensities of radiation at five different hours of the day during four different weeks of the year are shown in Figures 26-29. The graphs also show the range in intensity that is possible in these four weeks. At 0800 in the week of March 18-24, Figure 26, the cumulative probability is 40 percent that the radiation will equal 139.6 W/m^2 [200 x 10^{-3} cal/(cm^2 min)]. Figure 26 also shows that maximum and minimum values at 0800 during March 18-24 ranged from 0 to 349.5 W/m^2 [0 to 50.1 x 10^{-2} cal/(cm^2 min)] and that the median (50 percent) value is about 208.6 W/m^2 [29.9 x 10^{-2} cal/(cm^2 min)].

Two features in Figures 27-29 may require explanation. One is the segregation of solar radiation probabilities for the five different hours into two distinct periods. The 0800 and 1600 CST probabilities represent one period and the 1000, 1200, and 1400 CST values a second period. This segregation of the hourly values into two more or less separate periods is not as evident in the March 18-24 week as it is in the other three weeks. Since 0800 and 1600 CST are nearly equidistant from solar noon it is normal for them to show nearly equal radiation probabilities. However, for 1200 CST to have a level of radiation equal to 1000 and 1400 CST the noon cloud cover must be sufficiently common to suppress radiation to the 1000 and 1400 CST levels.

The biggest difference between the 0800 and 1600 CST radiation values in the four weeks shown occurs in the week of March 18-24. A part of this difference can be attributed to the fact that of these four weeks this is the week that has the greatest variation between local and solar time. Since the solar time lags local time, a greater amount of radiation will be received at 1600 than at 0800, and more at 1400 than at 1000 CST.

Figures 30-37 are intended to show radiation probabilities in terms of a continuous trace through the day. Traces start with the first full hour after sunrise and end with the last hour before sunset. The January 31-February 6 week, Figure 37, for example, shows that at solar noon (TST) the cumulative probability is 90 percent that the radiation will be less than or equal to 558.1 W/m^2 [80.0 x 10^{-2} cal/(cm^2 min)].

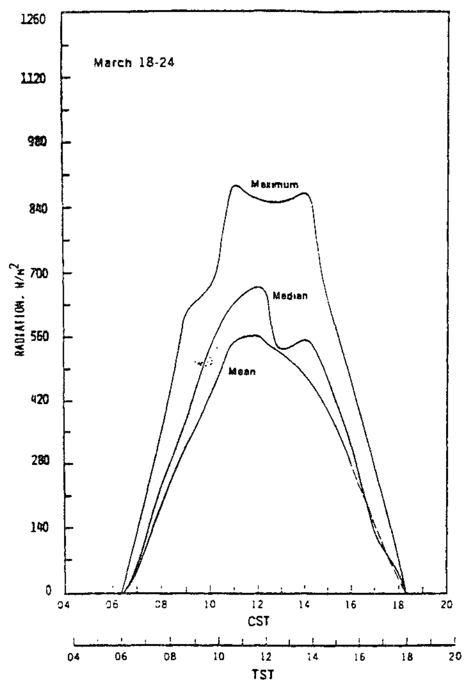

Figure 18. March 18-24.

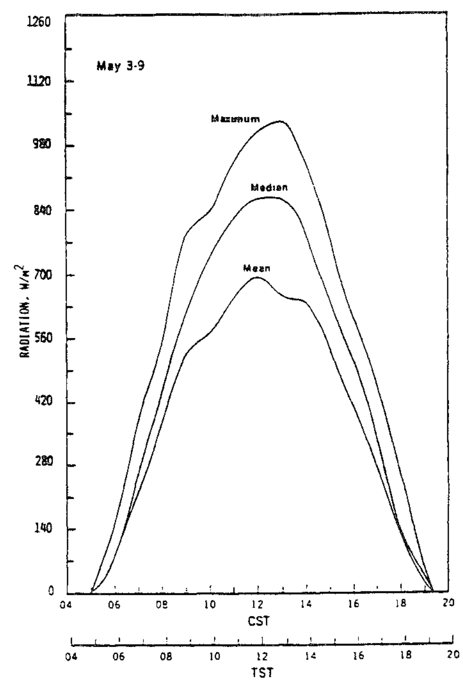

Figure 19. May 3-9.

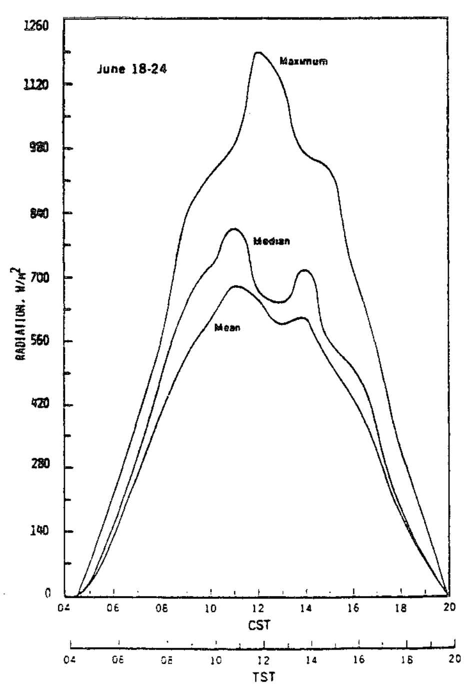

Figure 20. June 18-24.

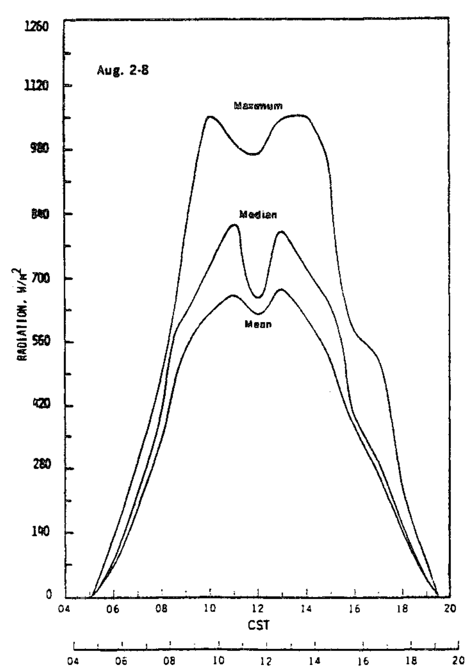

Figure 21. August 2-8.

Figures 18-21. Daily course of the mean, median, and maximum total solar radiation values during each week, St. Paul, 1971-1977.

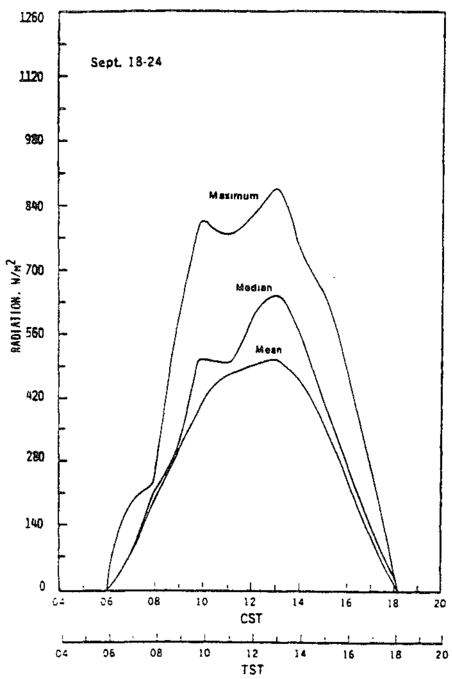

Figure 22. September 18-24.

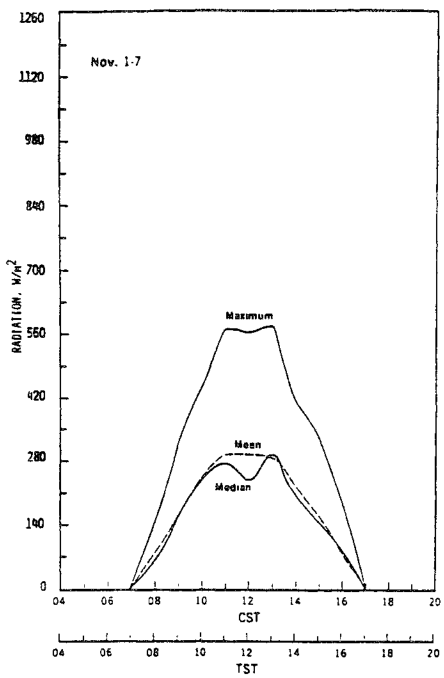

Figure 23. November 1-7.

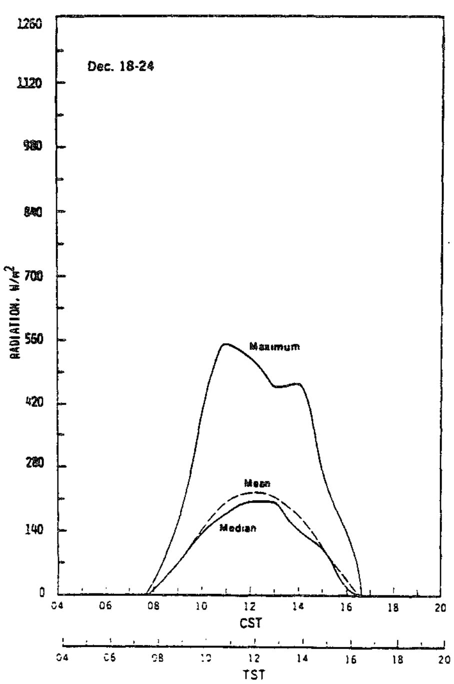

Figure 24. December 18-24.

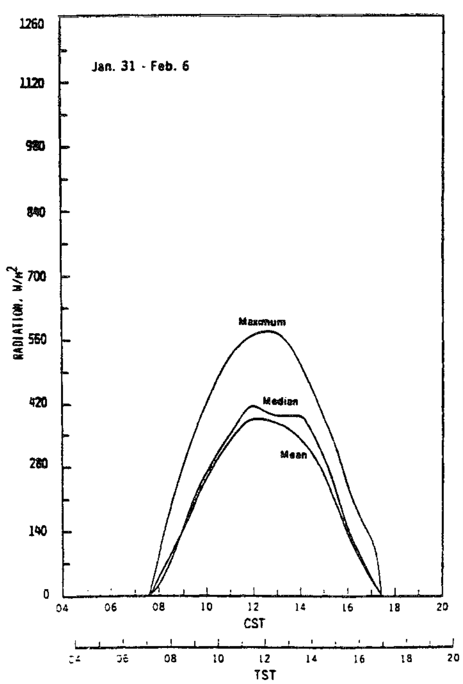

Figure 25. Jan. 31 - Feb. 6

Figures 22-25. Daily course of the mean, median, and maximum total solar radiation values during each week, St. Paul, 1971-1977.

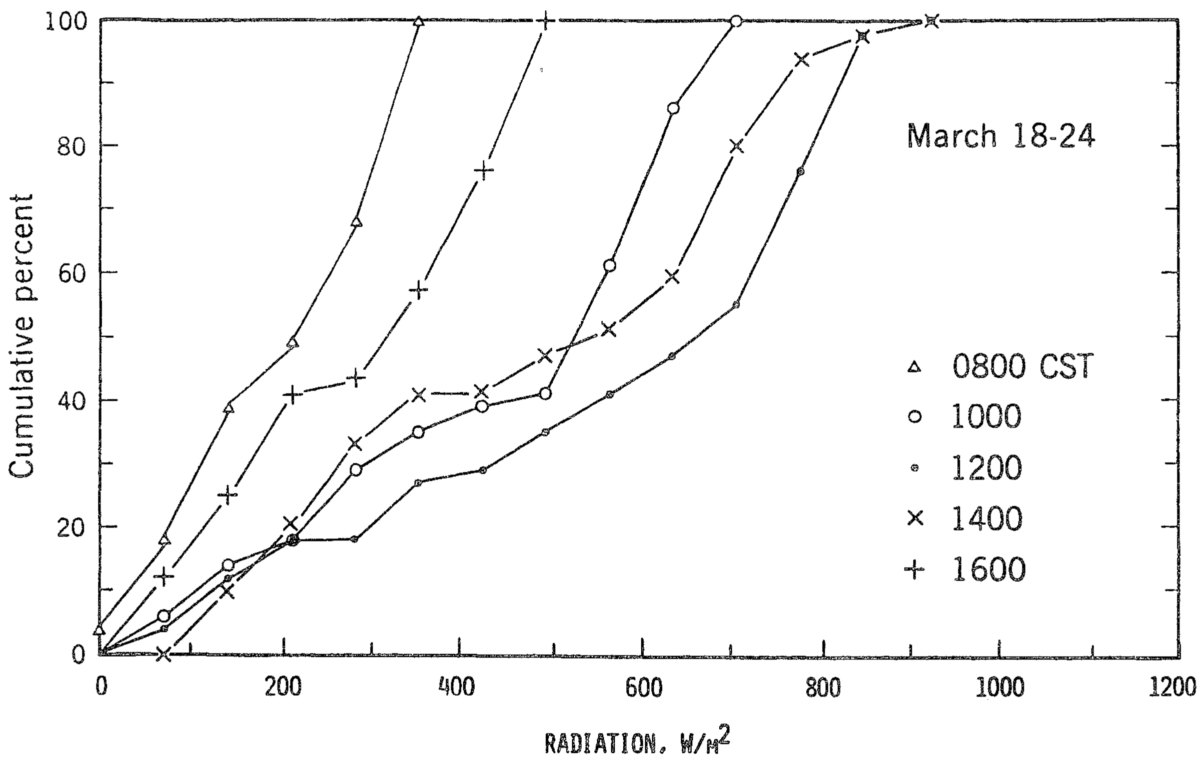

Figure 26. Mean cumulative percent frequency of hourly total solar radiation values at five different hours (CST) in the week of March 18-24, St. Paul, 1971-1977.

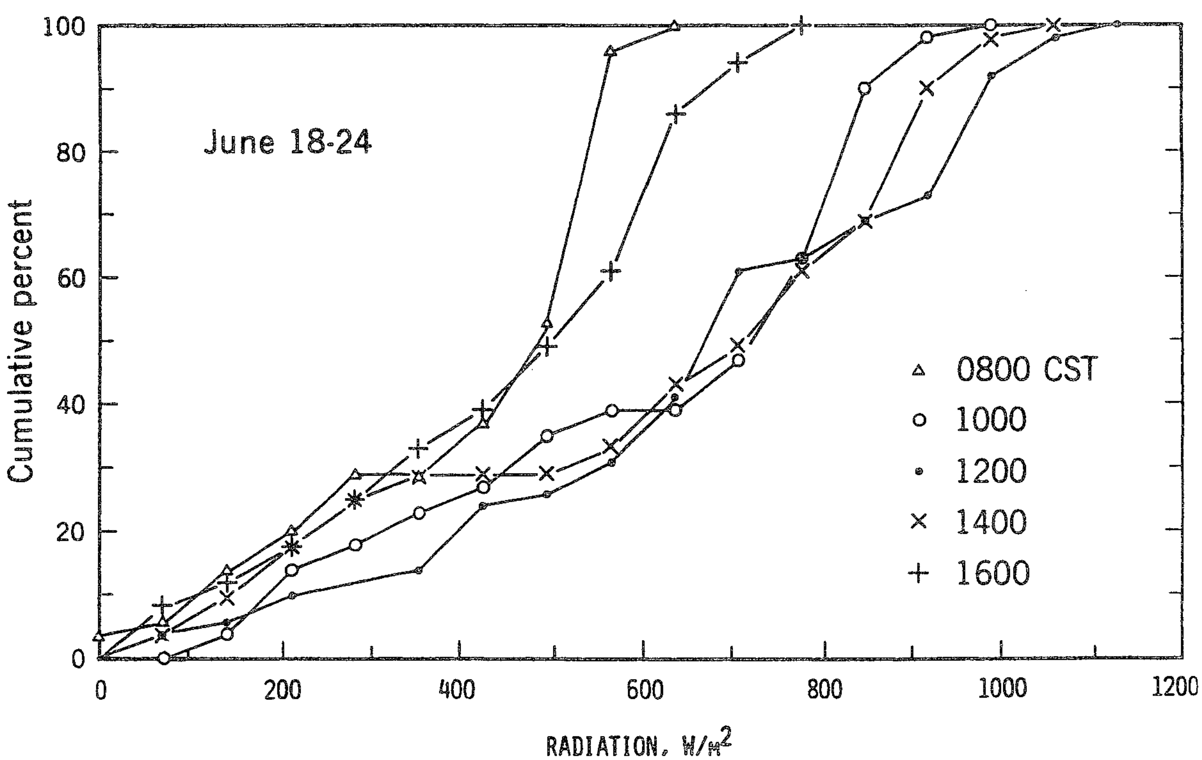

Figure 27. Mean cumulative percent frequency of hourly total solar radiation values at five different hours (CST) in the week of June 18-24, St. Paul, 1971-1977.

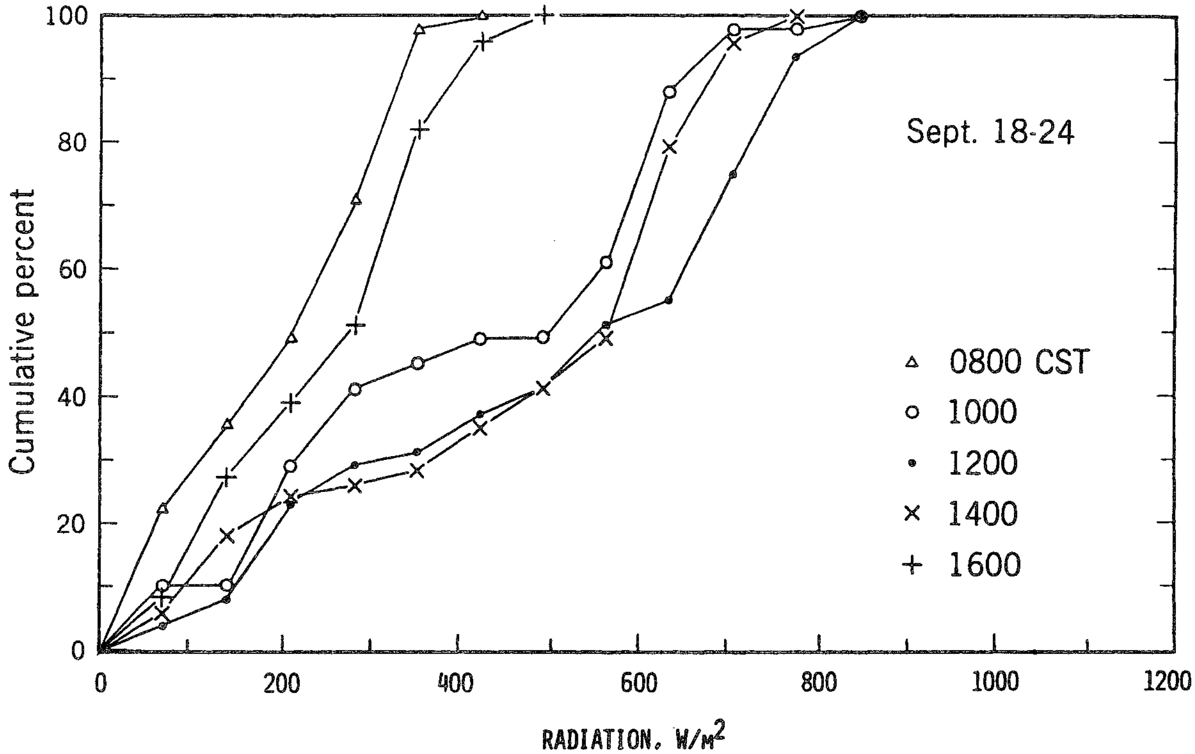

Figure 28. Mean cumulative percent frequency of hourly total solar radiation values at five different hours (CST) in the week of September 18-24, St. Paul, 1971-1977.

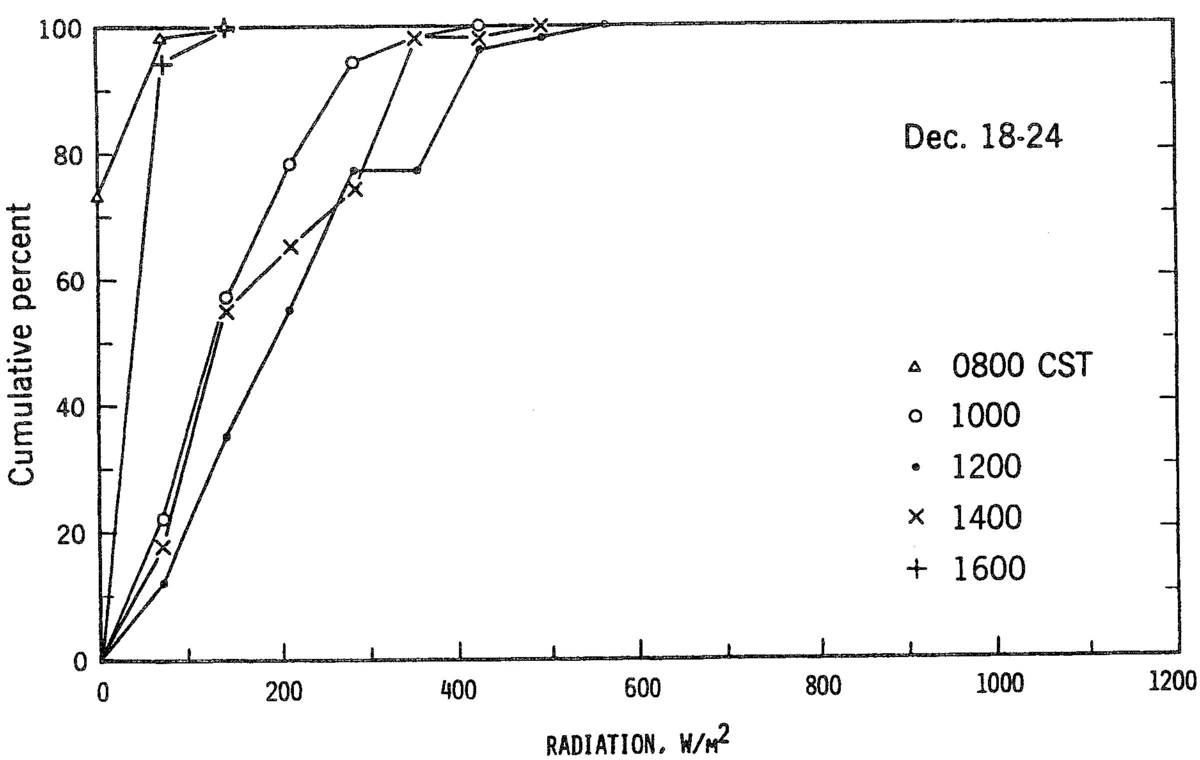

Figure 29. Mean cumulative percent frequency of hourly total solar radiation values at five different hours (CST) in the week of December 18-24, St. Paul, 1971-1977.

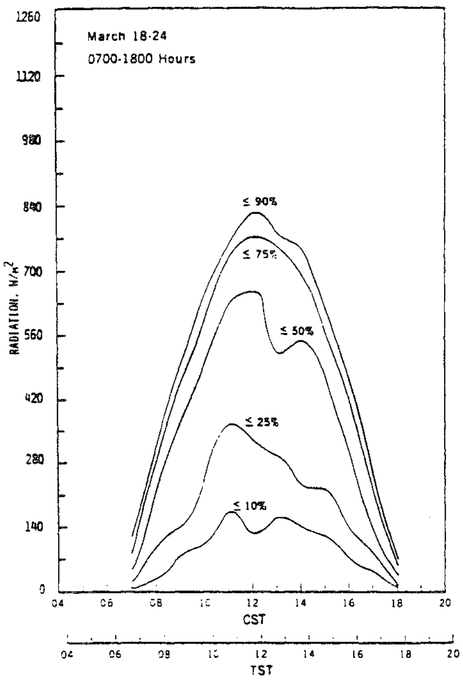

Figure 30. March 18-24.

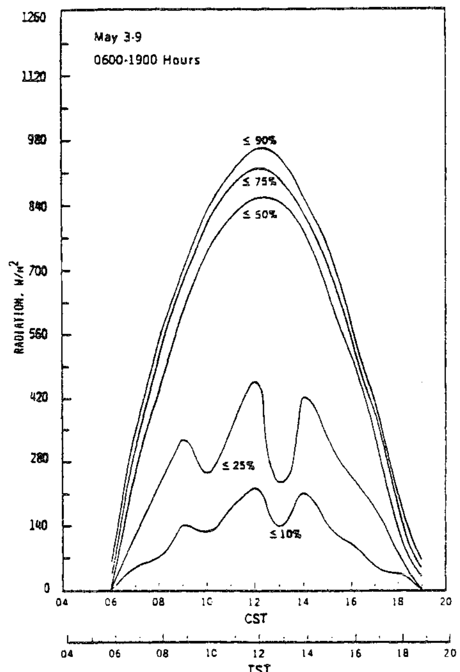

Figure 31. May 3-9.

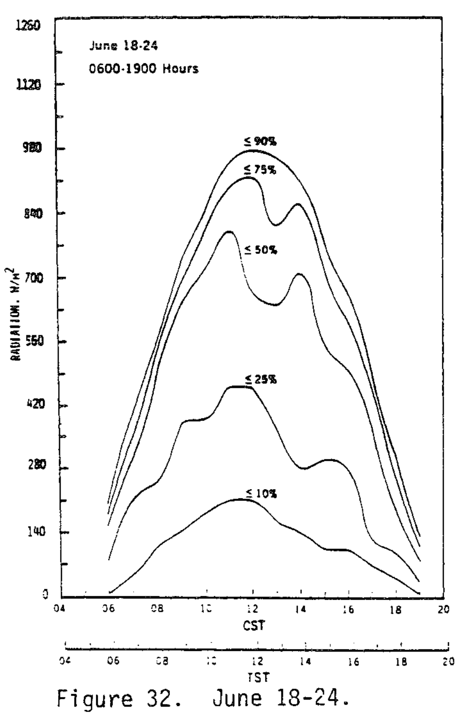

Figure 32. June 18-24.

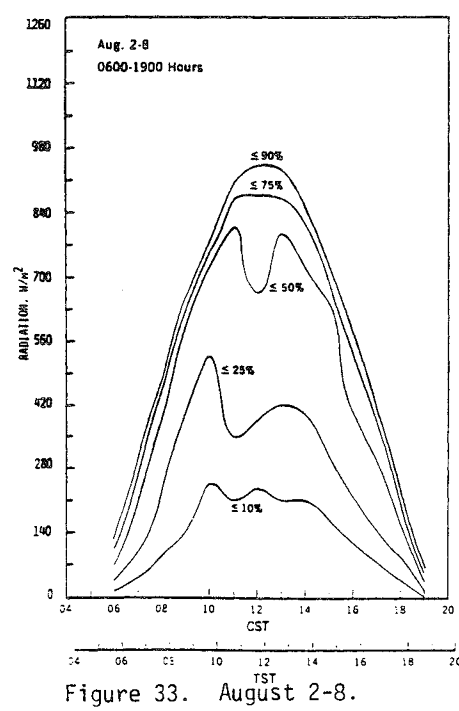

Figure 33. August 2-8.

Figures 30-33. The probability that the daily course of total solar radiation will not be exceeded during each week, St. Paul, 1971-1977.

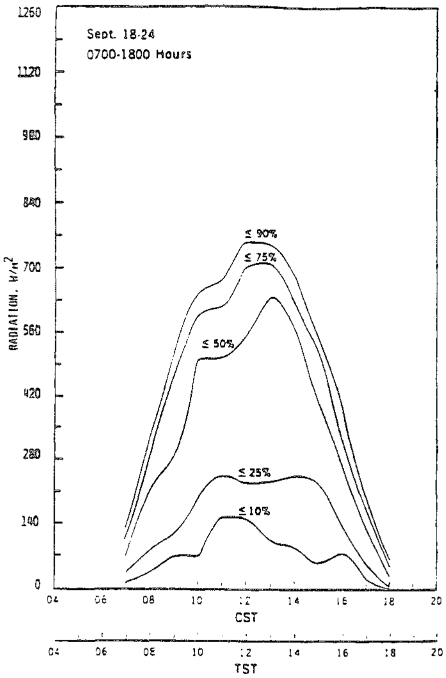

Figure 34. September 18-24.

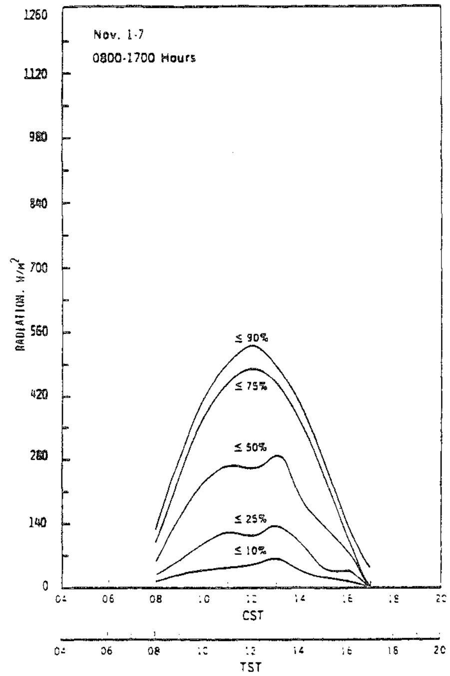

Figure 35. November 1-7.

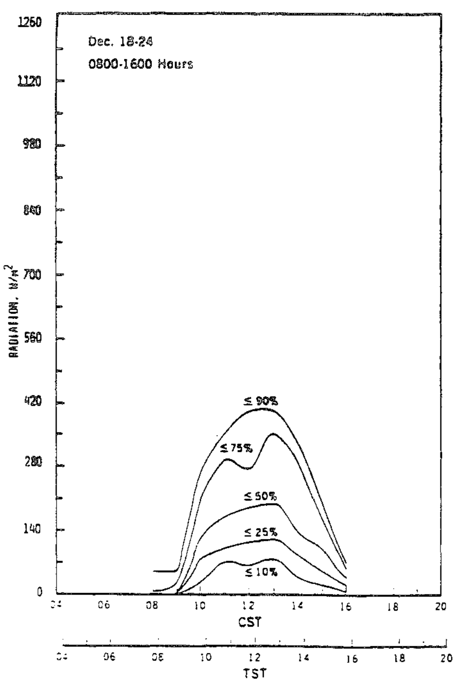

Figure 36. December 18-24.

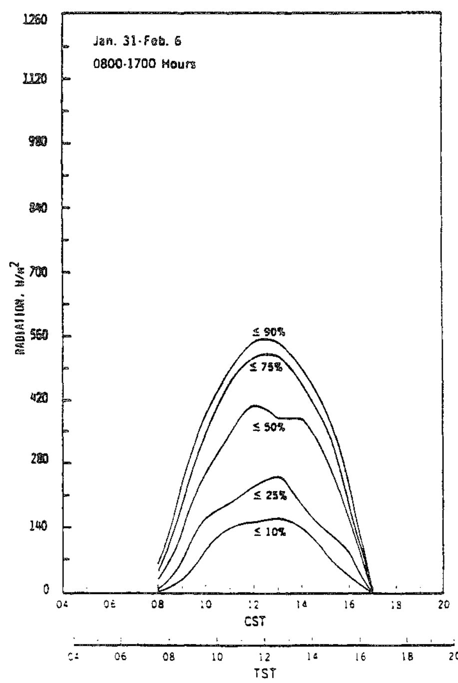

Figure 37. Jan. 31-Feb. 6

Figures 34-37. The probability that the daily course of total solar radiation will not be exceeded during each week, St. Paul, 1971-1977.

Annual and Seasonal Values

The annual and seasonal mean daily total solar radiation values for each year from 1963-1985 are shown in Figure 38, with associated statistics in Table 8. A typical summer day received almost three times as much radiation as a winter day. In spring, the daily reception was more than twice as great as in winter. Also, the mean daily radiation for a spring day was almost double that of a typical autumn day. This is not surprising because spring (March, April, and May) and autumn (September, October, and November), as defined, are not equally centered around their respective solstices (March 21 and September 22).

That the atmosphere had fewer summer clouds than usual during the 1976 drought is readily apparent in Figure 38. In spite of the variation in radiation values introduced by the drought, variation in daily amounts over the 1963-1985 record was greatest in the spring and least in the winter, as indicated by standard deviations listed in Table 8. When the relative variation (the coefficient of variation) is considered, however, the maximum is found in the autumn and the minimum in summer.

All seasons except spring showed a very slight downward trend with time for the 1963-1985 period. This is indicated by the linear trend regression coefficients listed in Table 8. None of the trends, including the annual one [-0.012 MJ/(m^2 day) per year] and the slight upward trend in the spring data, is statistically significant.

Table 8. Seasonal statistics of daily total solar radiation, St. Paul 1963-1985. Units are MJ/(m^2 day) except for the Coefficient of Variation which is in percent.

Season	Mean	Median	Range	Standard Deviation	Coefficient of Variation	Regression Coefficient
Spring	16.44	17.29	31.27	7.72	49.96	0.038
Summer	21.05	22.65	31.23	6.69	31.78	-0.054
Autumn	9.78	9.04	23.48	5.83	59.61	-0.026
Winter	7.03	6.95	17.79	3.61	51.35	-0.016

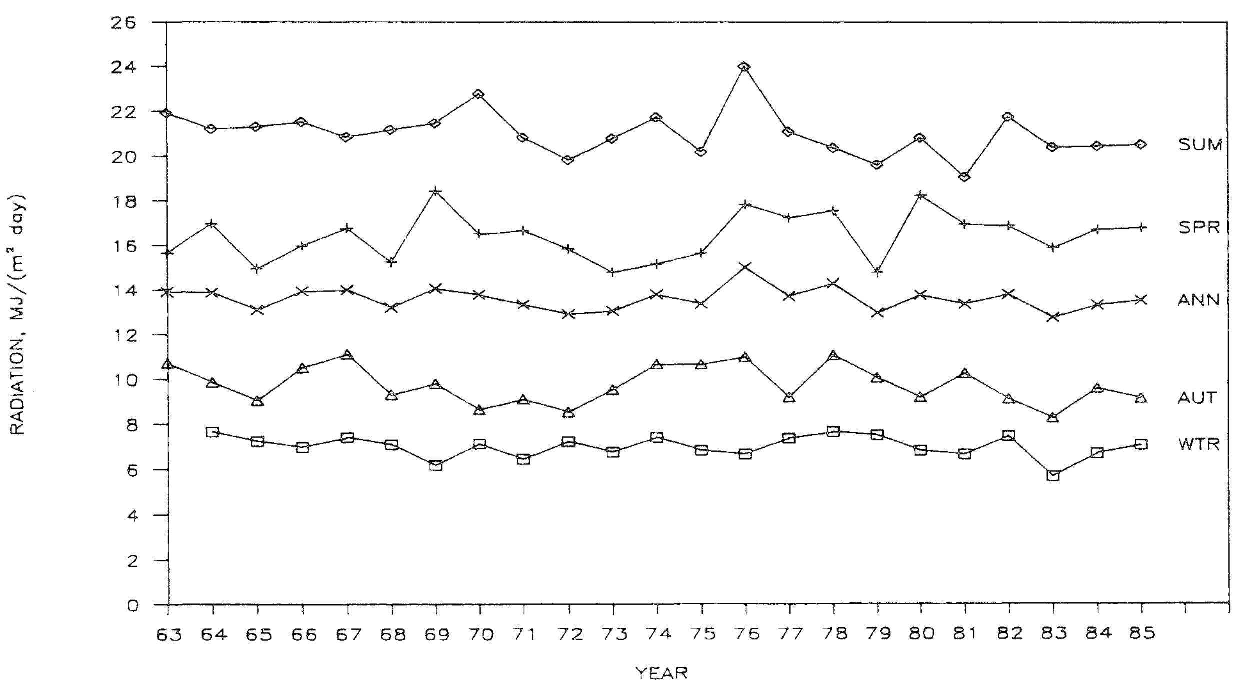

Figure 38. Annual and seasonal mean daily solar radiation for each year from 1963-1985.

Probabilities of Daily Total Radiation Reception

The probabilities in increments of 10 percent of receiving at least the indicated amounts of daily total solar radiation on a horizontal surface are listed in Table 9. These are the observed probabilities rather than those based upon a modeled set of data. The 50 percent probability value is also the median value. The standard error of the mean indicates the range within which the actual value can be expected to occur about 68 percent of the time.

Estimating Radiation Reception

Important as solar radiation is, it is measured at only a few sites. There presently are 10 automatic weather stations in Minnesota which do measure radiation, but these have been in place only since 1983. Until 1972 the National Weather Service (formerly the U.S. Weather Bureau) measured solar radiation at St. Cloud. This station had a lengthy and valuable record but was discontinued in 1972. Currently, only the St. Paul microclimate station has a continuous record of sufficient duration for analysis.

Because radiation is so important, but ordinarily measured at few sites, a number of methods has been developed to extend the measured data. This has been done in order to fill gaps in a radiation record, to extend a limited radiation record back in time, and to estimate radiation at sites where no measurements are made. A common and relatively successful method has been to correlate daily solar radiation totals with daily sunshine measurement values. Historically sunshine has been measured at more locations than has radiation, although the recent introduction of automatic weather stations is rapidly changing this situation. The regression equations used to equate the two variables have been both linear and curvilinear in nature. The former is usually more than satisfactory for most purposes.

Sunshine amount has been measured at the Minneapolis-St. Paul WSO AP for a number of years and provides a lengthy record to use with the solar radiation record at St. Paul. These two stations are separated by only 7.5 mi (12 km). The daily St. Paul radiation values for each week and month over the 1963-1985 record were correlated with the daily sunshine values at the airport. In figures 39-42 are shown the results obtained for January, April, July and October, respectively. The regression equations for each week, month, and season are listed in Table 10. The slopes of the best fit lines rise from a nearly horizontal position in winter to the steepest in July. This occurs because winter radiation has only a small range due to the short day length and the low sun angle, and the range in possible radiation values between 0 to 100 percent sunshine is small. Because the situation is reversed in summer with a greater amount of radiation for a given sunshine amount, the regression line is much steeper. The equations are of the form $Y = A + BX$, where A and B are constants, X is the measured daily percent sunshine, and Y is the predicted solar radiation in $MJ/(m^2\ day)$.

The confidence that can be placed in the estimated amount of radiation is indicated by the standard error of estimate. The true mean will be within the bounds of the standard error about 68 percent of the time.

A factor of concern is the distance from the sunshine station for which the estimated radiation value remains acceptable. The only study that can be cited in which an evaluation of the decrease in the correlation between sunshine and radiation can be estimated as the distance between the two sites increases is that of Baker and Skaggs (1984). This study was based on measurements of radiation and sunshine at a number of stations in the North Central region. It included Minnesota stations. Of initial interest is a feature they termed a "zone of indifference" that surrounds a locality where both measurements are made. Up to a distance of 36 mi (60 km) between paired sunshine and radiation stations, the correlation between the two variables was about 0.90. This is an indication of the insensitivity of the sunshine instrument, since only beyond this zone does the distance effect become apparent. Beyond the 36 mi (60 km) zone the correlation on an annual basis decreases about 0.12 per 60 mi (100 km). Thus, at a distance of about 160 mi (260 km) the correlation between daily sunshine and radiation values would be reduced to about 0.66 on an annual basis. The correlation is poorest in summer and best in the spring.

Table 9. Probability in percent of receiving at least the indicated amount of solar radiation, MJ/(m^2 day), based on the 1963-1985 St. Paul record. There are 161 observations per week.

FIRST DATE	STD ERR	90	80	75	70	60	50	40	30	25	20	10
3/01	0.42	3.4	5.2	6.4	7.5	10.2	12.6	14.6	15.9	16.4	17.0	17.4
08	0.43	5.1	7.4	8.4	9.7	11.8	15.0	16.6	17.7	18.0	18.3	19.0
15	0.49	4.3	6.2	7.3	8.2	11.6	15.3	17.5	18.5	18.8	19.6	20.1
22	0.48	4.8	8.3	9.7	11.5	14.2	17.0	18.3	19.4	19.7	20.1	21.2
29	0.55	4.5	6.8	8.2	9.4	13.1	16.3	18.5	20.7	21.4	21.6	22.8
4/05	0.55	5.4	8.2	9.3	10.3	13.3	16.7	20.1	22.1	22.7	23.1	23.7
12	0.61	3.5	6.9	8.2	9.3	13.1	16.3	18.8	21.7	22.4	23.4	24.7
19	0.65	4.3	8.0	9.8	11.0	15.4	19.3	22.4	24.5	24.7	25.5	26.2
26	0.63	5.9	9.7	11.6	13.2	15.9	19.3	22.0	25.0	25.7	26.2	27.1
5/03	0.58	8.2	11.4	15.1	16.5	18.5	21.0	23.7	25.9	26.6	26.8	28.1
10	0.65	6.3	8.3	11.5	13.9	18.4	21.5	23.4	26.0	26.3	27.0	28.1
17	0.62	9.0	12.7	14.0	16.3	19.6	23.1	24.4	26.5	27.2	27.8	29.2
24	0.63	8.0	12.1	13.4	15.3	18.8	22.2	24.2	26.2	26.9	27.8	29.8
31	0.56	10.8	15.0	17.1	18.5	21.3	24.0	26.0	27.2	27.8	28.5	29.7
6/07	0.58	9.8	14.1	16.2	18.4	20.3	22.8	24.6	26.7	27.5	28.4	30.0
14	0.54	11.3	13.8	15.1	17.0	19.8	21.4	24.5	26.4	27.2	27.5	29.0
21	0.60	9.9	13.7	15.6	17.7	20.4	24.3	26.5	27.5	27.9	28.7	29.7
28	0.49	13.9	18.6	20.1	21.5	23.9	25.9	27.2	28.0	28.5	29.0	29.8
7/05	0.48	14.0	19.3	20.8	22.3	24.4	25.5	26.6	27.2	27.9	28.2	29.1
12	0.47	11.5	17.1	18.5	20.5	22.6	23.8	25.1	26.4	26.7	27.0	28.0
19	0.45	13.6	17.9	19.8	21.1	22.7	23.9	25.5	26.6	26.8	27.3	28.6
26	0.44	12.6	15.9	17.5	18.3	20.3	22.1	23.4	24.8	25.2	25.9	27.1
8/02	0.42	13.9	17.1	18.3	19.9	21.3	23.1	23.9	24.9	25.4	25.9	26.6
09	0.45	11.4	15.4	16.5	18.5	20.3	22.0	23.5	24.5	24.8	25.0	25.9
16	0.49	8.1	12.2	13.1	14.8	17.2	20.1	21.4	23.1	23.4	24.2	24.9
23	0.54	5.7	8.1	9.3	11.5	15.0	18.5	20.3	21.5	22.0	22.5	23.9
30	0.44	7.9	11.3	11.8	13.9	15.4	18.0	20.1	21.1	21.4	21.7	22.6
9/06	0.47	5.7	8.3	10.3	11.8	15.2	17.2	19.3	20.0	20.3	20.6	21.1
13	0.48	4.4	6.4	7.9	10.0	12.8	15.6	17.3	19.1	19.3	19.6	20.3
20	0.48	3.5	4.9	6.1	7.0	11.9	14.7	16.3	17.5	17.8	18.2	19.0
27	0.39	4.6	7.2	8.4	9.3	11.5	13.1	15.0	16.4	16.7	17.1	17.5
10/04	0.39	2.7	4.4	5.0	6.2	8.5	10.0	12.7	14.6	15.1	15.3	15.9
11	0.37	2.7	4.0	4.8	6.0	9.6	11.5	12.8	13.5	13.6	14.0	14.6
18	0.34	2.4	3.5	4.4	5.2	6.7	9.8	10.9	11.9	12.6	12.9	13.5
25	0.29	2.4	4.3	5.3	5.9	8.0	9.5	10.5	11.1	11.4	11.7	12.3
11/01	0.27	2.1	3.2	3.9	4.7	6.2	7.9	9.0	9.8	10.2	10.6	11.1
08	0.26	1.3	2.3	2.8	3.1	4.3	4.9	6.4	8.5	8.8	9.3	10.0
15	0.22	1.7	2.5	2.9	3.1	4.2	5.4	6.2	7.5	8.3	8.5	9.0
22	0.20	1.5	2.2	2.4	3.1	3.8	4.9	5.8	7.0	7.4	7.7	8.4
29	0.19	1.6	2.5	2.8	3.1	3.7	4.8	5.6	6.5	7.0	7.4	8.0
12/06	0.17	1.9	2.6	2.8	3.2	3.9	4.8	5.5	6.5	6.8	7.1	7.5
13	0.18	1.6	2.2	2.6	3.1	4.2	5.2	6.0	6.7	6.9	7.2	7.7
20	0.18	1.8	2.3	2.6	2.9	3.6	4.6	5.9	6.6	6.9	7.1	7.6
27	0.18	1.9	2.6	3.1	3.4	4.2	5.4	6.3	7.0	7.2	7.5	7.9
1/03	0.18	2.5	3.8	3.9	4.5	5.4	6.6	7.2	7.7	7.9	8.1	8.4
10	0.18	3.1	3.9	4.3	4.8	5.8	6.5	7.1	7.7	8.1	8.3	9.2
17	0.20	2.8	3.9	4.6	5.3	6.3	7.5	8.1	8.5	8.7	9.0	9.4
24	0.21	3.2	4.6	5.8	6.3	7.2	8.0	8.7	9.5	9.8	10.1	10.6
31	0.25	3.8	5.5	6.8	7.4	8.7	10.0	10.6	11.1	11.3	11.6	12.1
2/07	0.26	4.1	5.7	7.2	7.8	9.5	10.5	11.2	11.9	12.2	12.4	12.9
14	0.30	4.1	5.6	6.5	7.2	8.6	10.0	11.4	12.6	13.3	13.7	14.3
21	0.34	4.1	7.5	9.0	9.9	11.5	12.6	13.7	14.4	14.6	14.9	15.6

Table 10. Weekly, monthly, and seasonal linear regression equations of daily sunshine percent versus daily total solar radiation. The sunshine values are from the Minneapolis - St. Paul WSO AP and the radiation values, MJ/(m^2 day), from the St. Paul microclimate station, 1963-1985.

DATE	r^2	EQUATION	STANDARD ERROR	DATE	r^2	EQUATION	STANDARD ERROR
			Week				
3/01	0.84	Y = 4.04 + 0.13 X	2.13	8/30	0.82	Y = 5.07 + 0.17 X	2.35
08	0.82	Y = 5.24 + 0.13 X	2.29	9/06	0.86	Y = 5.22 + 0.16 X	2.26
15	0.90	Y = 4.62 + 0.16 X	1.94	13	0.88	Y = 4.65 + 0.16 X	2.14
22	0.86	Y = 5.02 + 0.17 X	2.26	20	0.90	Y = 3.49 + 0.15 X	1.91
29	0.84	Y = 4.66 + 0.18 X	2.80	27	0.87	Y = 3.91 + 0.14 X	1.80
4/05	0.89	Y = 5.12 + 0.18 X	2.38	10/04	0.88	Y = 3.98 + 0.12 X	1.74
12	0.88	Y = 3.97 + 0.21 X	2.69	11	0.89	Y = 3.61 + 0.12 X	1.54
19	0.90	Y = 4.02 + 0.22 X	2.56	18	0.88	Y = 3.58 + 0.11 X	1.49
26	0.88	Y = 4.11 + 0.23 X	2.71	25	0.84	Y = 3.59 + 0.09 X	1.49
5/03	0.84	Y = 5.69 + 0.22 X	2.96	11/01	0.88	Y = 3.07 + 0.09 X	1.21
10	0.81	Y = 4.51 + 0.23 X	3.65	08	0.86	Y = 2.72 + 0.08 X	1.21
17	0.83	Y = 5.19 + 0.24 X	3.25	15	0.82	Y = 2.84 + 0.07 X	1.21
24	0.79	Y = 6.59 + 0.22 X	3.67	22	0.80	Y = 2.69 + 0.07 X	1.15
31	0.72	Y = 6.41 + 0.22 X	3.72	29	0.74	Y = 2.75 + 0.06 X	1.21
6/07	0.76	Y = 5.73 + 0.24 X	3.57	12/06	0.77	Y = 2.73 + 0.05 X	1.05
14	0.70	Y = 6.51 + 0.22 X	3.76	13	0.84	Y = 2.31 + 0.06 X	0.93
21	0.79	Y = 6.84 + 0.22 X	3.53	20	0.82	Y = 2.49 + 0.05 X	0.96
28	0.82	Y = 6.57 + 0.23 X	2.66	27	0.84	Y = 2.65 + 0.06 X	0.91
7/05	0.73	Y = 7.78 + 0.21 X	3.15	1/03	0.77	Y = 3.02 + 0.05 X	1.09
12	0.71	Y = 6.96 + 0.21 X	3.25	10	0.73	Y = 3.47 + 0.05 X	1.19
19	0.75	Y = 6.32 + 0.21 X	2.85	17	0.81	Y = 3.53 + 0.06 X	1.09
26	0.72	Y = 5.49 + 0.21 X	2.97	24	0.83	Y = 3.54 + 0.07 X	1.11
8/02	0.71	Y = 5.92 + 0.20 X	2.85	31	0.85	Y = 4.01 + 0.08 X	1.21
09	0.80	Y = 5.15 + 0.20 X	2.55	2/07	0.84	Y = 4.34 + 0.09 X	1.31
16	0.79	Y = 5.91 + 0.18 X	2.88	14	0.80	Y = 4.92 + 0.09 X	1.69
23	0.88	Y = 4.71 + 0.19 X	2.33	21	0.85	Y = 4.24 + 0.11 X	1.66
			Month				
January	0.75	Y = 3.35 + 0.06 X	1.29	July	0.72	Y = 6.63 + 0.21 X	3.16
February	0.78	Y = 4.44 + 0.09 X	1.81	August	0.81	Y = 5.13 + 0.20 X	2.78
March	0.82	Y = 4.69 + 0.15 X	2.56	September	0.83	Y = 4.42 + 0.16 X	2.47
April	0.87	Y = 4.42 + 0.20 X	2.77	October	0.85	Y = 3.68 + 0.11 X	1.81
May	0.82	Y = 5.54 + 0.23 X	3.39	November	0.81	Y = 2.80 + 0.08 X	1.35
June	0.75	Y = 6.43 + 0.23 X	3.56	December	0.80	Y = 2.57 + 0.05 X	1.01
			Season				
Spring	0.75	Y = 4.91 + 0.19 X	3.86	Autumn	0.70	Y = 3.23 + 0.13 X	3.21
Summer	0.73	Y = 6.02 + 0.21 X	3.47	Winter	0.63	Y = 3.14 + 0.08 X	2.21

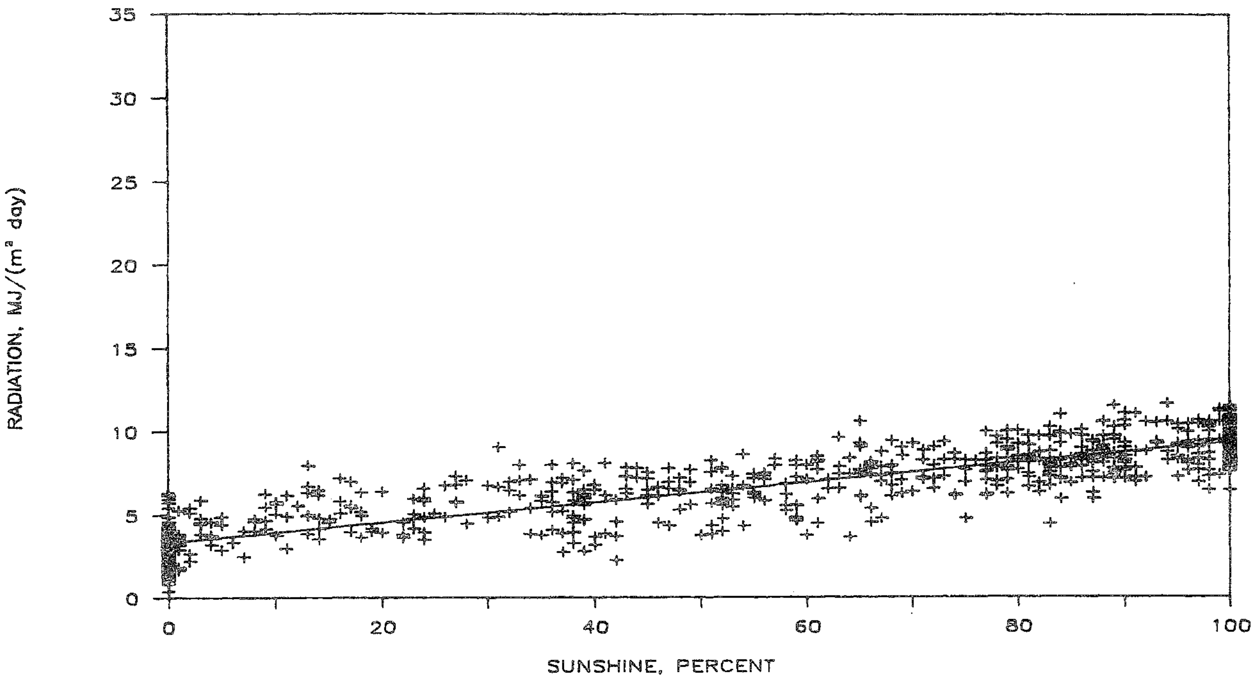

Figure 39. Daily total solar radiation at St. Paul and the associated sunshine percent at the Minneapolis-St. Paul WSO AP, 1963-1985, for January. The linear regression line is also shown.

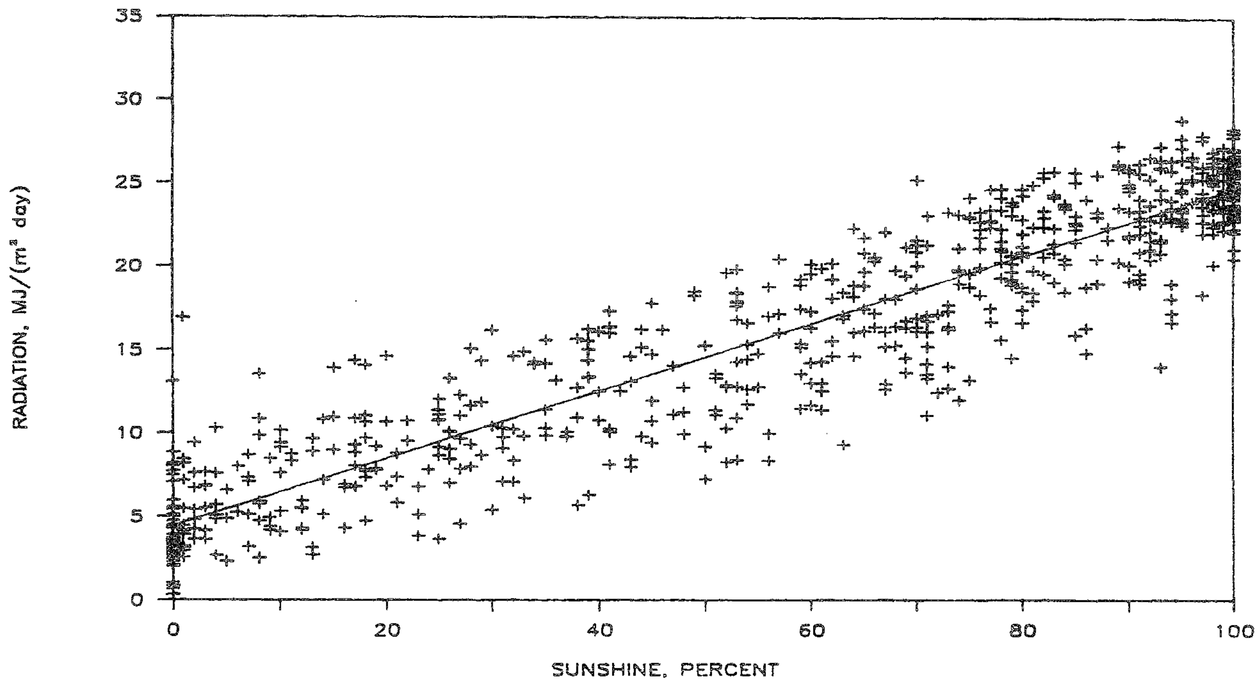

Figure 40. Daily total solar radiation at St. Paul and the associated sunshine percent at the Minneapolis-St. Paul WSO AP, 1963-1985, for April. The linear regression line is also shown.

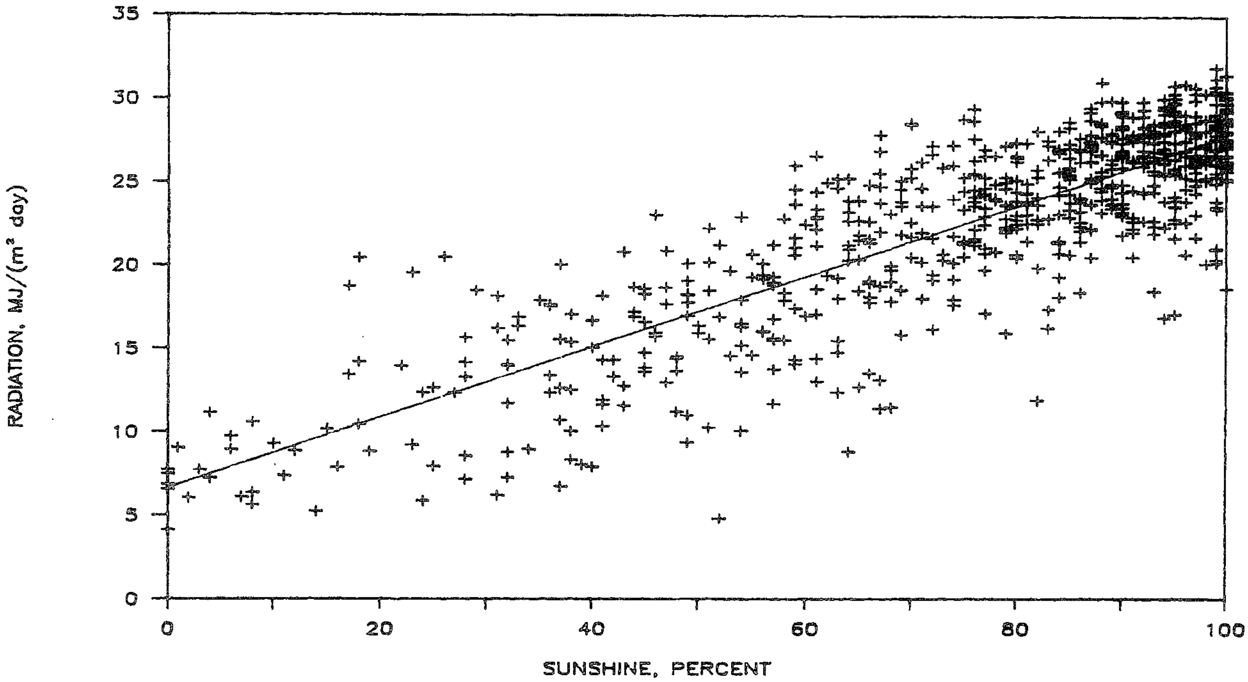

Figure 41. Daily total solar radiation at St. Paul and the associated sunshine percent at the Minneapolis-St. Paul WSO AP, 1963-1985, for July. The linear regression line is also shown.

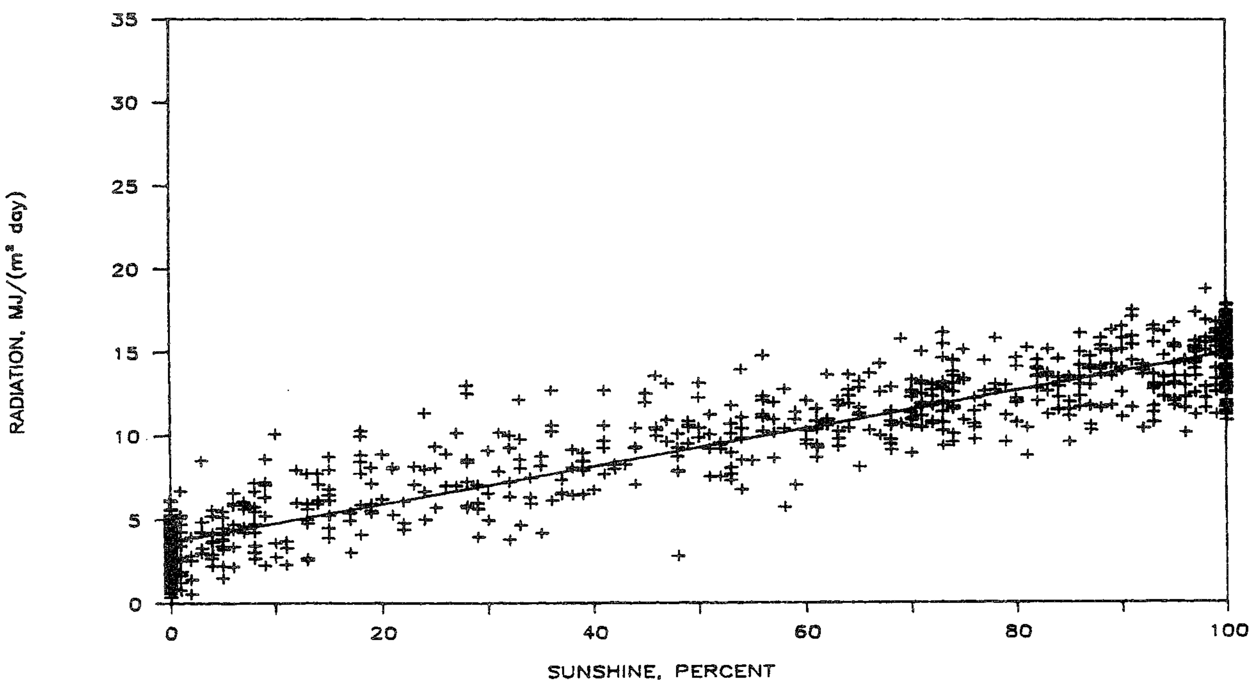

Figure 42. Daily total solar radiation at St. Paul and the associated sunshine percent at the Minneapolis-St. Paul WSO AP, 1963-1985, for October. The linear regression line is also shown.

RADIATION RECEIVED ON NON-HORIZONTAL SURFACES

South-Facing and 55° From The Horizontal

This orientation of the pyranometer is similar to many stationery solar collectors at this latitude. The 55° angle from horizontal is a compromise between summer and winter angular positions of the earth relative to the sun. This is an effective way of increasing the intensity of solar rays in winter when they are at a smaller angle with respect to horizontal surfaces, yet still have a reasonable radiation intensity in summer when solar rays are at their peak. For example, at 45°N the solar altitude at noon on June 21 reaches a maximum of 68.5° relative to a horizontal surface and a minimum of 21.5° on December 21. For the 55° south-facing surface the noon solar altitude is reduced to 56.5° on June 21 but is increased to 76.5° on December 21. At the equinoxes of March 21 and September 22, the noontime altitude angle for the 55° south-facing surface is 80° compared to only 45° on the horizontal surface. For many solar heating purposes this altitude change results in a more efficient use of solar radiation, particularly in the winter.

It is shown in Figure 43 how the mean daily radiation received on a 55° south-facing surface differs from the radiation incident on a horizontal surface at St. Paul on a weekly basis. The tilted surface receives a more uniform annual distribution of the solar radiation. For example, on June 21 the radiation on the 55° surface has been reduced to about 80 percent of that on a horizontal surface, while in the winter the ratio has been raised to a maximum of about 170 percent of the horizontal surface. The data in both Figures 43 and 44 have been smoothed with a 9-week running mean because the record period for these measurements extended only from September 1, 1979-August 21, 1984.

Shown in Figure 44 is a running mean of radiation reception on both the horizontal and 55° south-facing surfaces. The winter time advantage of the 55° south-facing surface is quite evident. The crossovers between radiation reception of the two surfaces occur in early April and late August.

Weekly radiation values of the 55° tilted pyranometer are in Table 11. These values include the maximum, minimum, and the ratio of maximum values to those obtained with a horizontally oriented pyranometer.

South-Facing and 90° From The Horizontal

Comparisons of the actual values and ratios of the 90° south-facing surface with a horizontally oriented surface are listed in Table 11 and ratios of the two surfaces in Figure 45. These ratios are much more extreme than those obtained with the 55° orientation. They range on clear days from a maximum that is about 300 percent greater at the winter solstice, December 21, to only about 60 percent of the horizontal surface at the summer solstice, June 21. A comparison of the actual values of radiation received on a 90° south-facing surface and on a horizontal surface is shown in Figure 46. The record period for these measurements was only August 22, 1984-December 31, 1985, and of necessity some data points have been estimated.

Normal Incidence Direct Beam

The pyrheliometer, with the aid of a motor driven gear box, is oriented so that the receiving surface is always normal to the solar rays. It has been in operation only since July 27, 1980. This is less than the required duration in most months for a stable frequency distribution of daily radiation values (Skaggs *et al.*, 1982). Also, the great frequency of clouds severely limits the useful information available, since their presence between the sun and the instrument for an extended period effectively nullifies a measurement. As a result, it has been necessary to reconstruct some values in order to obtain an estimate of the annual march of the normal incidence clear-day radiation totals, Figure 47. The ratios of maximum and average-day normal incidence direct beam radiation to the total direct and diffuse radiation on a horizontal surface are shown in Figure 48. The average-day ratios are almost consistently less than one, because clouds eliminate the direct beam radiation, and the diffuse radiation is not measured by the pyrheliometer. The weekly clear-day ratios are listed in Table 11, column 7.

The equation for the best fit line for the clear-day normal incidence radiation (Y) is:

[Equation 8]

$$Y = [28.87 + 9.77(A) - 4.19(B)]\ \mathrm{MJ/(m^2\ day)}.$$

Standard error of Y estimate = $2.59\ \mathrm{MJ/(m^2\ day)}$ and r^2 is 0.87.

A and B are defined as noted in Equation 3.

Table 11. Mean daily normal direct beam, 55°, and 90° solar radiation and associated values for each climatological week at St. Paul. Radiation values are MJ/(m^2 day). *

	Normal direct beam - 7/27/80 - 12/31/85							55° total radiation - 9/01/79 - 8/21/84							90° total radiation - 8/22/84 - 12/31/85						
FIRST DATE	MAX	MIN	MEDIAN	MEAN	STD DEV	RATIO	N	MAX	MIN	MEDIAN	MEAN	STD DEV	RATIO	N	MAX	MIN	MEDIAN	MEAN	STD DEV	RATIO	N
3/01	28.42	0.00	10.97	13.39	10.95	0.90	24	28.30	2.09	15.99	16.25	8.75	1.27	35	26.12	1.93	9.63	11.77	8.75	1.09	7
08	30.01	0.00	17.25	14.94	11.11	0.88	29	29.42	2.43	19.51	17.63	7.74	1.21	35	23.98	3.81	22.14	19.01	7.21	1.19	7
15	34.07	0.00	1.05	11.41	13.15	0.61	27	26.62	2.60	18.08	14.84	9.41	1.09	35	20.22	15.15	19.42	18.61	1.79	0.99	7
22	33.95	0.00	17.50	14.64	10.73	0.79	32	27.71	3.43	21.56	18.36	7.61	1.13	35	18.12	2.47	5.57	7.04	5.24	0.70	7
29	30.26	0.00	3.81	9.49	11.44	0.48	31	25.74	1.88	13.19	14.45	8.53	0.99	35	26.58	4.56	10.42	12.42	7.83	0.80	7
4/05	33.96	0.00	6.24	10.96	11.65	0.56	28	28.38	3.31	11.51	14.33	8.15	0.98	35	17.29	9.79	14.57	14.52	2.44	0.72	7
12	35.20	0.00	7.83	11.36	11.16	0.56	27	29.26	2.43	20.59	17.25	9.31	0.98	35	16.70	0.92	13.35	10.26	6.38	0.60	7
19	35.79	0.00	12.10	15.04	12.33	0.67	25	27.00	2.51	23.90	19.38	7.31	0.95	35	15.82	3.06	11.05	10.18	4.62	0.62	7
26	35.33	1.84	23.23	18.14	12.13	0.78	20	25.95	4.60	21.10	18.63	6.42	0.90	35	15.57	6.49	13.69	11.54	4.38	0.57	7
5/03	38.09	0.00	12.31	13.65	12.24	0.59	21	25.41	4.44	18.63	17.10	6.67	0.87	35	15.03	5.99	13.19	12.57	3.23	0.55	7
10	34.62	0.00	10.93	11.65	10.42	0.56	21	30.68	5.23	19.05	17.92	6.57	0.87	35	13.60	3.35	4.19	6.53	4.11	0.56	7
17	35.75	0.00	19.25	17.90	12.28	0.71	18	25.12	2.97	20.39	17.43	7.08	0.85	35	14.11	2.22	13.69	11.72	4.33	0.48	7
24	31.77	0.21	9.00	12.16	10.22	0.53	11	24.53	5.69	15.74	15.41	6.46	0.81	35	12.85	5.44	9.54	9.52	2.52	0.50	7
31	35.71	2.60	13.86	17.04	10.62	0.72	23	24.45	7.91	17.96	17.36	4.68	0.80	35	13.10	5.48	8.50	9.10	2.90	0.48	7
6/07	33.32	0.00	15.15	15.85	11.87	0.66	30	24.45	7.91	15.40	16.40	5.54	0.79	35	12.93	3.81	11.13	9.92	3.44	0.46	7
14	28.09	1.26	9.84	11.55	8.21	0.57	23	23.36	4.69	16.83	16.13	5.45	0.78	35	12.06	4.19	10.05	8.74	2.87	0.49	7
21	39.89	0.00	22.35	18.07	12.84	0.71	27	23.48	3.43	20.43	17.02	6.19	0.80	35	12.60	5.15	11.51	9.79	3.11	0.46	7
28	39.18	0.00	24.28	22.82	10.86	0.85	29	23.98	3.56	20.05	18.48	5.46	0.80	35	12.43	10.46	12.10	11.77	0.70	0.46	7
7/05	34.83	0.46	25.28	22.60	9.78	0.87	28	23.98	4.23	20.93	19.47	4.78	0.80	35	12.93	7.49	12.60	11.61	1.93	0.45	7
12	35.83	0.29	16.20	17.65	10.97	0.73	24	23.82	6.28	19.67	17.37	5.32	0.82	35	13.19	5.94	10.51	10.13	2.59	0.48	7
19	40.69	1.47	21.47	20.72	13.08	0.82	16	23.78	8.58	18.21	17.30	4.40	0.83	35	13.56	3.98	13.39	12.08	3.57	0.47	7
26	35.58	0.59	19.80	18.42	9.76	0.79	25	24.70	5.78	19.25	17.98	5.03	0.85	35	14.44	6.61	12.14	11.23	2.78	0.52	7
8/02	35.12	4.35	16.03	18.07	8.88	0.82	23	23.40	8.41	18.50	18.18	4.31	0.88	35	14.57	4.56	12.01	10.96	4.12	0.54	7
09	33.65	0.25	18.46	17.39	10.76	0.80	33	25.20	4.98	19.55	17.53	5.46	0.90	35	15.53	2.51	14.02	11.55	5.19	0.56	7
16	33.78	1.30	11.89	14.43	9.95	0.74	33	25.78	5.61	19.00	17.70	6.25	0.94	34	15.74	4.73	9.17	9.22	3.41	0.59	8
23	30.43	0.00	12.72	12.69	9.39	0.69	33	24.11	3.98	14.48	13.68	6.63	0.96	28	16.07	2.18	12.14	10.28	5.36	0.65	14
30	31.69	0.00	12.26	14.94	11.60	0.81	30	25.32	4.40	19.30	17.42	6.94	1.03	33	17.71	2.68	9.08	9.67	5.53	0.67	14
9/06	34.45	0.00	14.06	14.38	10.50	0.83	34	25.95	3.60	19.59	16.73	7.50	1.07	35	18.42	3.77	10.51	11.17	4.67	0.74	14
13	29.34	0.00	11.22	12.78	10.46	0.79	41	26.20	0.59	15.57	14.93	7.82	1.08	35	18.71	4.40	17.20	14.71	5.27	0.86	14
20	30.10	0.00	12.43	12.73	10.75	0.81	41	25.91	3.26	19.17	16.74	7.84	1.19	35	19.46	1.17	10.17	9.65	6.64	0.80	14
27	30.31	0.00	7.79	11.16	10.18	0.79	41	25.28	2.26	13.23	13.11	7.01	1.20	35	20.80	1.59	15.40	13.70	6.89	0.95	14
10/04	30.51	0.00	2.93	8.25	9.91	0.63	39	25.12	1.67	13.44	13.20	8.42	1.23	35	15.36	1.05	4.60	5.96	4.88	0.75	14
11	27.38	0.00	2.43	8.15	9.66	0.69	40	24.36	1.84	11.68	12.77	8.06	1.31	30	19.80	0.71	3.10	7.47	7.32	0.84	14
18	26.54	0.00	2.09	8.00	9.09	0.71	37	18.54	1.72	7.12	8.72	6.20	1.26	33	20.64	0.75	11.09	10.69	8.15	1.06	14
25	25.20	0.00	14.73	13.08	9.33	1.22	35	22.94	1.72	17.08	13.96	7.84	1.46	35	19.13	0.67	14.15	12.61	6.27	1.31	14
11/01	25.58	0.00	5.78	9.64	9.35	1.00	33	22.14	0.92	9.25	10.66	6.62	1.43	35	20.55	0.92	16.91	13.19	7.56	1.37	14
08	22.52	0.00	0.17	6.30	8.52	0.70	37	21.68	0.46	4.73	8.68	7.73	1.34	35	19.05	0.75	4.19	7.91	7.15	1.10	14
15	23.44	0.00	3.98	7.49	8.57	0.96	36	20.51	0.04	9.46	9.45	7.02	1.44	35	20.39	0.29	8.83	10.37	6.60	1.48	14
22	22.27	0.00	2.05	5.89	7.24	0.80	33	20.34	0.75	5.27	8.19	6.64	1.43	35	18.17	1.05	5.15	7.58	6.39	1.34	14
29	21.60	0.00	0.08	3.86	7.01	0.54	36	21.47	0.25	6.36	8.08	6.14	1.49	35	22.52	0.33	2.89	7.45	8.43	1.34	14
12/06	18.75	0.00	2.26	5.24	5.86	0.81	41	18.71	1.34	8.92	8.70	5.29	1.63	35	19.13	1.55	7.49	9.38	6.84	1.55	14
13	20.76	0.00	5.61	7.74	7.82	1.09	39	19.67	0.21	12.14	10.36	6.69	1.72	35	21.52	0.84	12.93	11.61	7.66	1.82	14
20	20.68	0.00	3.06	6.08	7.02	0.90	36	19.84	0.13	6.95	8.48	6.35	1.59	35	20.80	1.21	9.38	10.26	7.36	1.72	14
27	20.59	0.00	6.28	7.55	7.56	1.06	36	18.71	0.71	7.83	8.52	6.32	1.57	35	21.26	0.08	11.55	11.70	7.91	1.78	12
1/03	21.39	0.00	6.20	8.27	7.66	1.15	34	20.39	1.17	8.33	9.39	5.79	1.62	35	20.13	3.26	19.34	14.87	7.92	2.05	7
10	23.15	0.00	8.66	8.44	7.41	1.06	34	20.89	1.17	11.22	10.49	6.35	1.63	35	20.59	3.73	15.70	12.06	7.53	1.70	7
17	24.07	0.00	11.26	10.78	7.76	1.27	34	21.05	2.05	15.15	13.26	6.39	1.74	35	21.85	3.64	16.83	15.91	6.51	1.87	7
24	23.65	0.00	4.56	7.43	8.00	0.85	29	22.73	1.72	12.81	13.00	6.99	1.62	35	22.94	3.73	10.51	11.75	7.77	1.42	7
31	24.32	0.00	12.26	11.71	9.60	1.06	23	24.32	2.64	17.87	15.57	7.31	1.62	33	22.52	8.79	15.74	15.85	6.30	1.53	7
2/07	26.66	0.00	2.13	9.39	10.46	0.76	25	24.36	2.26	16.53	13.62	8.23	1.41	28	25.20	3.64	12.93	14.33	8.76	1.36	7
14	27.63	0.00	3.22	6.86	8.24	0.59	28	25.41	1.97	8.46	11.04	7.81	1.27	33	24.99	10.13	16.37	17.44	5.81	1.48	7
21	28.63	0.00	5.23	8.89	9.81	0.65	24	26.45	1.05	16.91	15.18	8.45	1.34	35	18.59	1.42	2.60	7.18	7.03	0.82	7

* N is the number of values in each week.

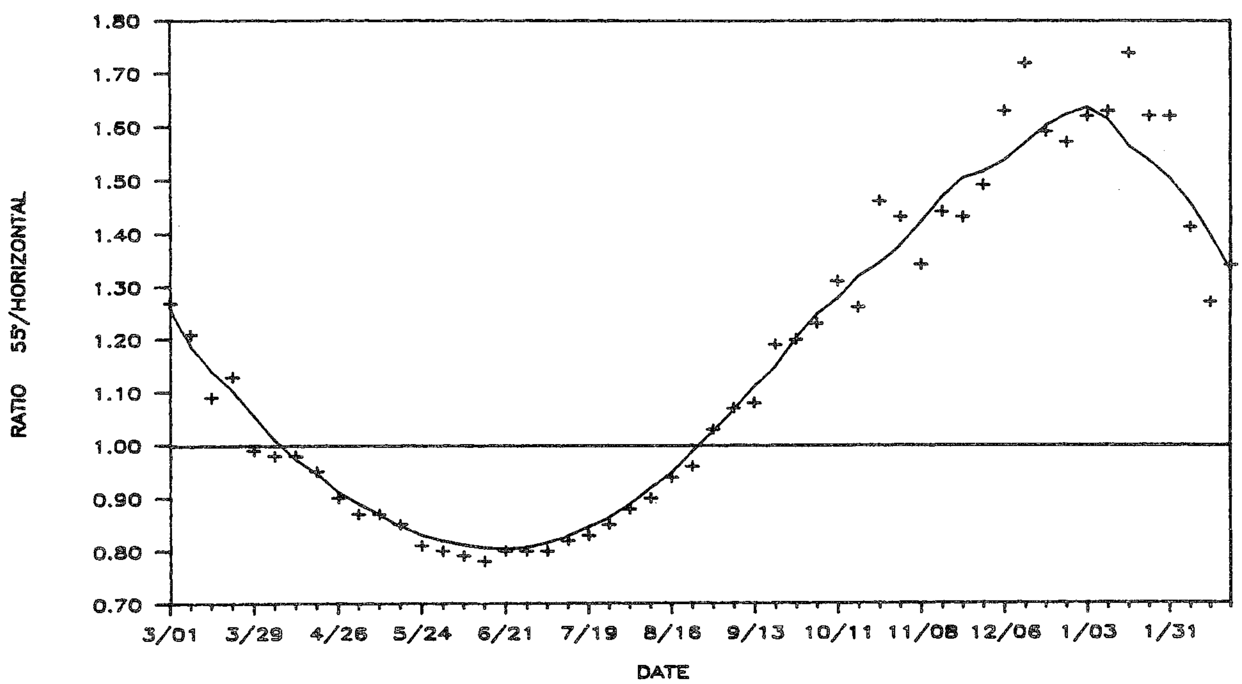

Figure 43. Mean weekly ratio of the daily total solar radiation received on a 55° south-facing surface to that received on a horizontal surface, St. Paul, September 1, 1979-August 21, 1984. The curve is the 9-week running mean.

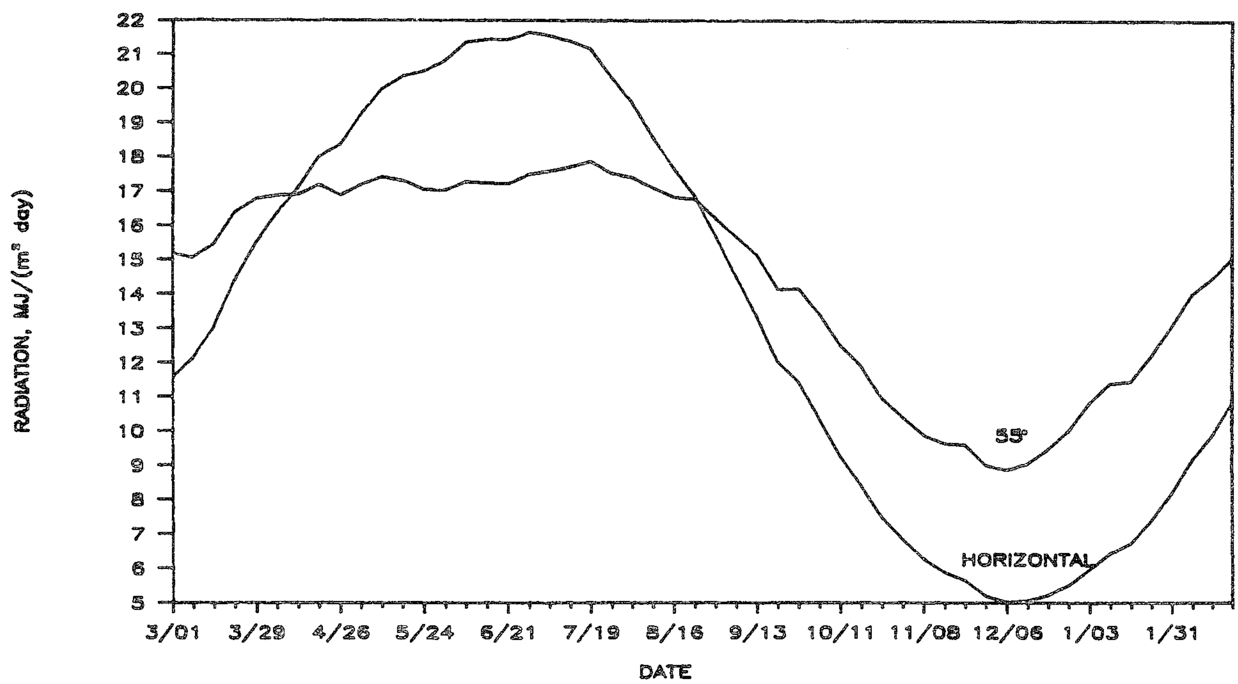

Figure 44. Mean daily total solar radiation on a weekly basis received on a 55° south-facing surface and on a horizontal surface. The data have been smoothed with a 9-week running mean. Both data sets are for the period September 1, 1979-August 21, 1984.

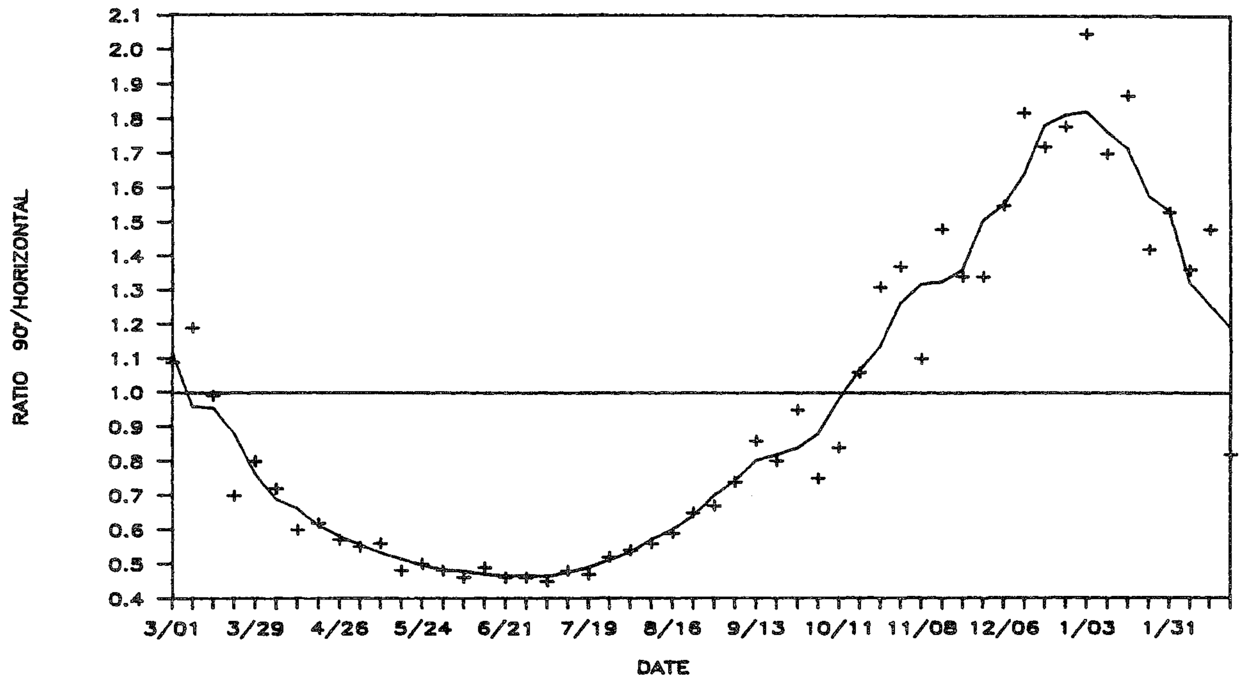

Figure 45. Mean weekly ratio of the daily total solar radiation received on a 90° south-facing surface August 22, 1984-December 31, 1985, to that received on a horizontal surface 1963-1985, at St. Paul.

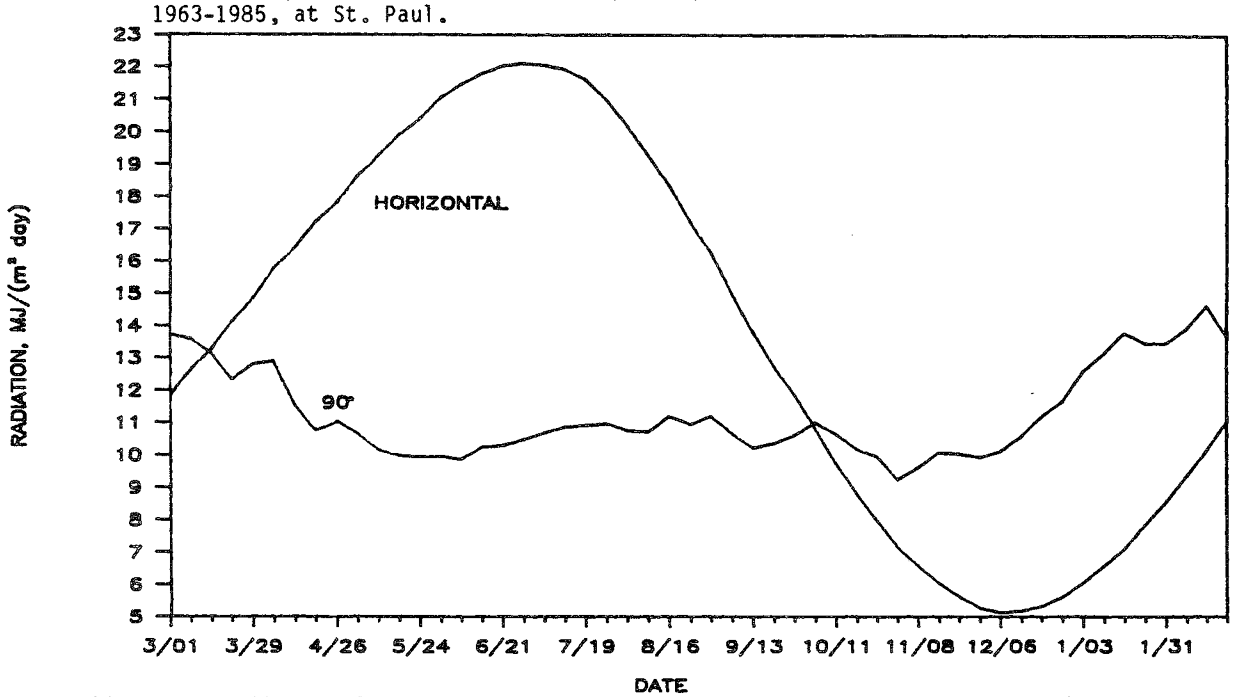

Figure 46. Mean daily total solar radiation on a weekly basis received on a 90° south-facing surface St. Paul, August 22, 1984-December 31, 1985, and on a horizontal surface, St. Paul 1963-1985. The data have been smoothed with a 9-week running mean. Due to brevity of the 90° south-facing radiation record some data points have been estimated.

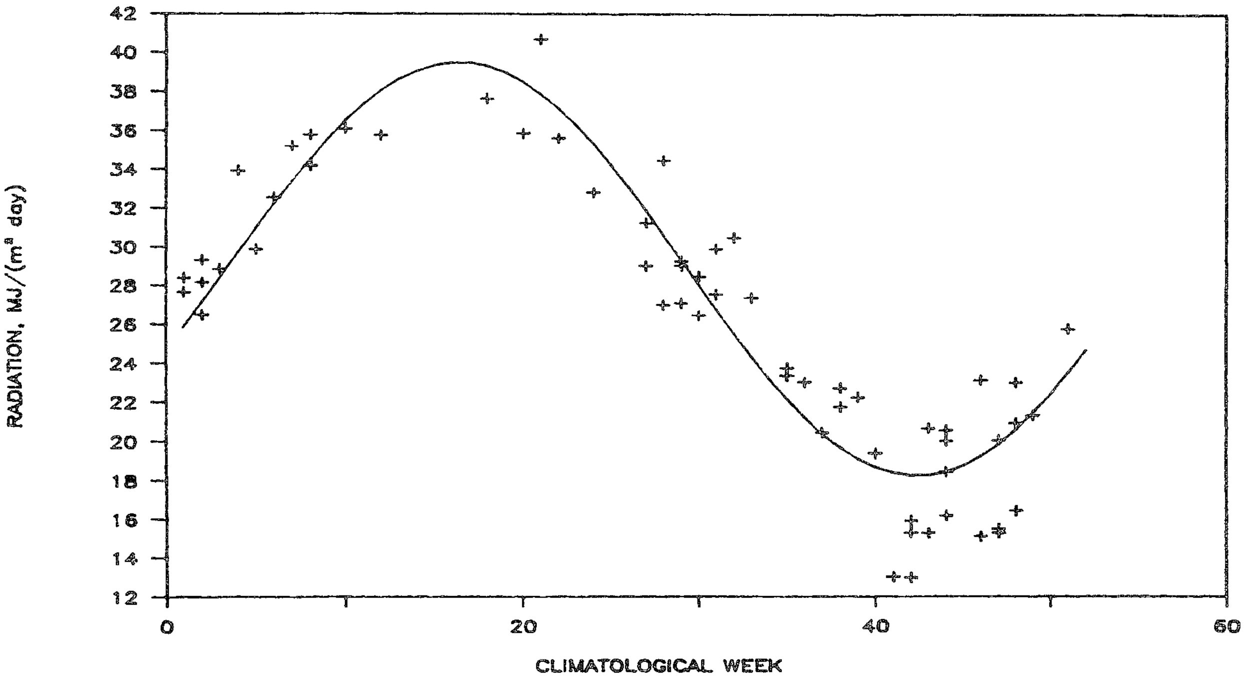

Figure 47. Clear-day normal incidence solar radiation and the best-fit line of the values, St. Paul, July 27, 1980-December 31, 1985. March 1-7 = Week 1, July 12-18 = Week 20, November 29-December 5 = Week 40.

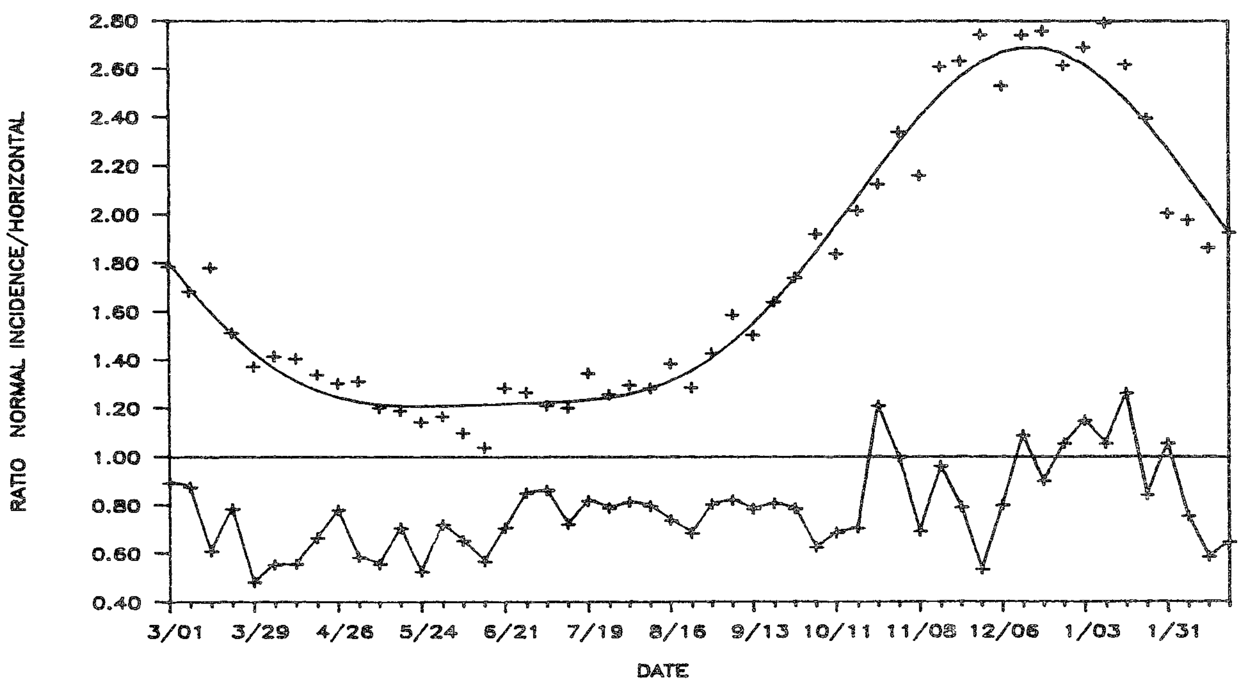

Figure 48. Maximum (top) and mean (bottom) ratios of the normal incidence daily solar radiation to the daily total solar radiation received on a horizontal surface, St. Paul, July 28, 1980-December 31, 1985.

REFLECTED RADIATION

Terms

No object absorbs all of the radiation incident upon it. Some radiation may be transmitted and a portion is always reflected. Reflectivity of a surface, according to Monteith (1973), is the fraction of the solar radiation incident upon a surface that is reflected at a specific wavelength. The more general term is reflection coefficient. This represents the average reflectivity over a given waveband, weighted according to the distribution of radiation in the solar spectrum. Often the word albedo serves as a synonym for reflection coefficient, and that is how albedo is used here. (Albedo is occasionally also applied to the fraction of the visible radiation (0.4-0.7 µm) which is reflected.) More simply, albedo, or the reflection coefficient, is the ratio of the solar radiation reflected by the body to the solar radiation incident upon that body. The ratio is usually expressed as a percentage.

The albedo of a region, place, or particular surface is important because it is an energy ratio. It is one component of the net energy exchange between an object and space, since for opaque surfaces it represents the amount of solar radiation that is not absorbed. As a result, the higher the albedo, the poorer is the linkage between an object and its solar environment.

General Conditions

Albedos of four different plant canopies were measured for a total of 5778 days, Table 12. The longest measurements were over sod. The grass was mowed to keep it at an approximate 3 in (7.6 cm) height. The sod is a permanent part of the station site and is primarily Kentucky blue grass (*Poa pratensis* L.). About 6 years of measurements were made over the sod cover. An adjoining plot measuring 58.8 ft by 49.2 ft (17.9 m by 15.0 m) was used for the 3 other vegetative surfaces: alfalfa (*Medicago sativa* L.) and soybeans (*Glycine max* L.) for about 5 years each, and green peas (*Pisum sativum* L.) for one season only.

Soil is extremely important in terms of agricultural albedos. At certain times and conditions it may be partially or entirely exposed. As a result it is necessary to consider the physical characteristics of the soil which provide the background to these measurements. The soil at the station is a Waukegan silt loam, a mixed mesic Typic Hapludoll, consisting of approximately 30 in (76 cm) of loessial silt loam overlying coarse sandy gravel outwash material. The plant available water holding capacity is 6 in (15 cm) in the top 39 in (1 m). The color description of the topsoil is very dark brown (Munsell color: 10YR 2/2) in the moist condition and dark grayish brown (Munsell color: 10YR 4/2) for the dry condition (Handley, 1983). Organic matter content is 3.5%.

Albedo measurements were made over one surface at a time and therefore lack the desirable feature of representing the same climatic conditions. Nevertheless, due to the number of observations obtained of all surfaces, except the peas, the measurements are believed to provide an adequate sample.

Special Measurement Considerations

During certain snowfall days a special problem of high albedos was encountered that must be common, but which has not been noted in the literature to our knowledge. This was the deposition of snow on the dome of the upright pyranometer resulting in reduced incoming radiation reception and, therefore, unduly high albedos. In fact, almost all occasions of daily albedos greater than 90 percent arose from this circumstance. Such days were usually, but not always, characterized by low wind speeds and a moderate to heavy snowfall. This problem can apparently only be controlled by nearly constant brushing of the snow off the dome. Since we neither developed an instrument for automatic snow removal nor could afford constant observer attendance, this problem could be dealt with only after the fact. Incoming solar radiation was adjusted by the previously described albedo method.

Table 12. Total number of days of albedo measurements for each surface sampled.

	Days Per Month												
Cover	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Sod	230	225	248	218	173	150	155	172	200	240	220	228	2459
Alfalfa	124	113	124	120	155	150	155	155	131	124	120	124	1595
Soybeans	124	114	124	142	156	150	155	155	149	124	120	124	1637
Peas	0	0	0	0	12	30	31	14	0	0	0	0	87
Total	478	452	496	480	496	480	496	496	480	488	460	476	5778

In reviewing the literature it was found that Budyko (1974) listed fresh, dry snow as having an albedo range of 80-95 percent and Langham (1981) gave 92-98 percent for fresh snow. These values are probably acceptable for instantaneous values. However, at St. Paul, snow had fallen on almost every day in which we calculated a daily albedo greater than 90 percent. As a result of our experience, any daily value greater than 90 percent, in spite of the just cited albedo measurements, is questionable. Because snow occurred at St. Paul at temperatures down to at least -4°F (-20°C), our reluctance to accept daily albedos greater than 90 percent is not a matter of our lacking samples of a low density, "dry" snow with a high albedo.

Frost is also a problem. However, in most cases its presence resulted in an enhancement of the measured radiation due to internal reflection within the radiometer dome. Only in the case of heavy frost was a reduction in the measured radiation noted. The removal of the frost from the bulb resulted in an obvious change in the recorder pen trace, and a correction in the radiation could be made easily.

Mean Daily, Monthly, Seasonal, and Annual Albedos

Distributions of the albedo values for January and July are shown in Figure 49. Winter and summer distributions of the albedos are almost the reverse of the incoming solar radiation distributions. January radiation values are very limited in range and quite low in amount due to the short days and low sun angle, while albedo values are negatively skewed due to the broad range of values and the greater frequency of high albedos.

From Figure 50 or Table 13 it is apparent that there are really only two seasons with respect to albedo values. One is the snow season of about three months with an average albedo of 69 percent. The other period, and the major one in terms of duration, is the April-October no-snow season with monthly means ranging from only about 19 percent in May to 23 percent in October. The transitional months between the snow and no-snow seasons generally are March and November, with mean albedo values of 44 and 39 percent, respectively.

That the winter represents a separate season with respect to albedo values is very well illustrated in Figure 51. Except for the winters of 1979-80 and 1980-81, none of the albedo values are less than 60 percent. Indeed the winter season average is 69 percent, and the median is 77 percent, Table 13. Spring, summer, and autumn are more or less alike, although summer does exhibit the lowest and most uniform albedo, as a result of the nearly total plant cover. One year, 1975, shows up as quite unusual with the albedo 10.6 percent above the 36.5 percent annual mean, Figure 52. This high albedo was due in particular to the above average spring and autumn albedos, Figure 51, resulting from the late spring and early autumn snow cover. The winter albedo was also high, averaging nearly 80 percent, but it was not much different from four other winters, 1970-1971, 1978-1979, 1981-1982, and 1983-1984.

Table 13. Mean monthly, seasonal, and annual albedo statistics at St. Paul, November 21, 1969-December 31, 1985. The data include all four surfaces.

Period	Mean	Median	Range	Standard Deviation	Coefficient of Variation	Normalized to April Mean
January	74	79	76	16.3	21.9	3.36
February	69	74	84	18.8	27.3	3.14
March	44	37	89	28.1	64.0	2.00
April	22	18	86	16.2	73.4	1.00
May	19	21	48	6.2	31.8	0.86
June	20	21	28	4.6	22.9	0.91
July	21	21	23	3.3	15.3	0.95
August	22	22	27	3.1	14.1	1.00
September	22	22	31	4.2	19.4	1.00
October	23	24	48	5.8	25.5	1.05
November	39	27	84	24.8	63.4	1.77
December	64	75	85	24.2	37.9	2.91
Spring	29	20	89	22.0	77.1	1.32
Summer	21	22	28	3.8	18.0	0.95
Autumn	28	24	89	16.7	60.6	1.27
Winter	69	77	85	20.5	29.7	3.14
April-Oct.	21	22	88	7.5	35.4	0.95
May-Sept.	21	22	48	4.5	21.6	0.95
May-Aug.	21	21	48	4.6	22.1	0.95
Annual	36	24	92	25.5	70.4	1.64

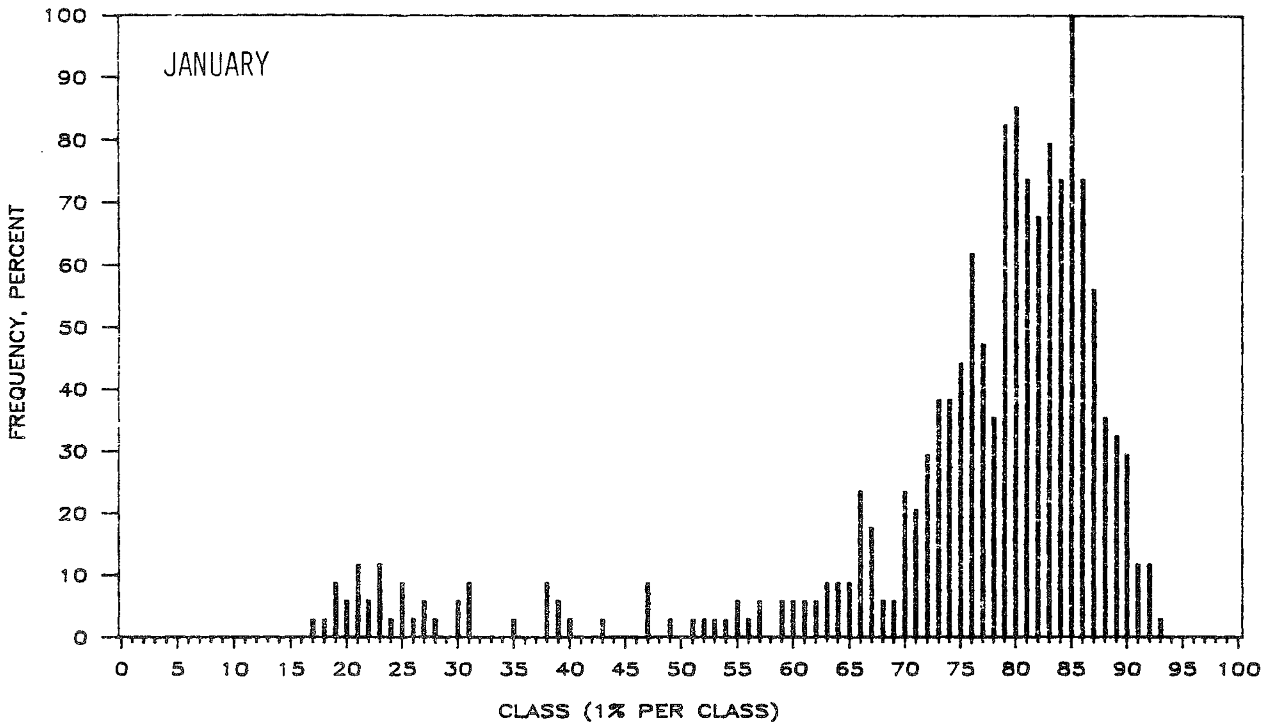

Figure 49. January frequency distributions of daily albedo, St. Paul, 1969-1985.

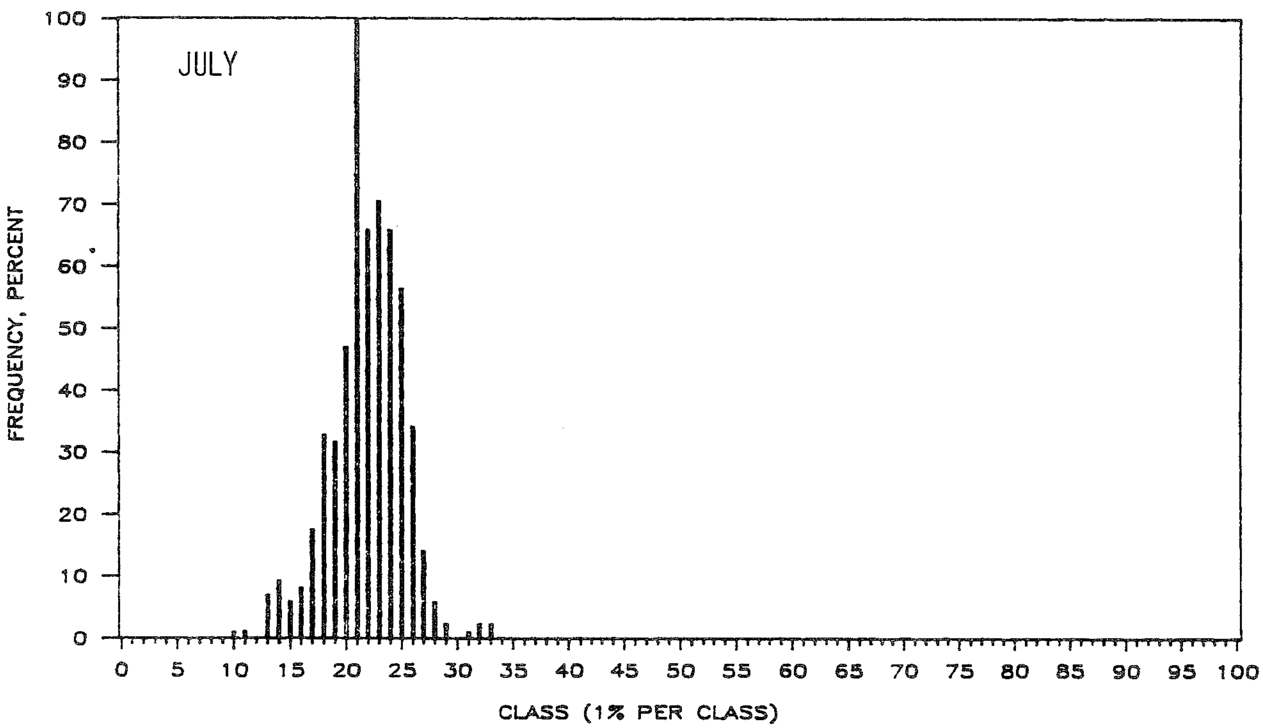

Figure 49. July frequency distributions of daily albedo, St. Paul, 1969-1985.

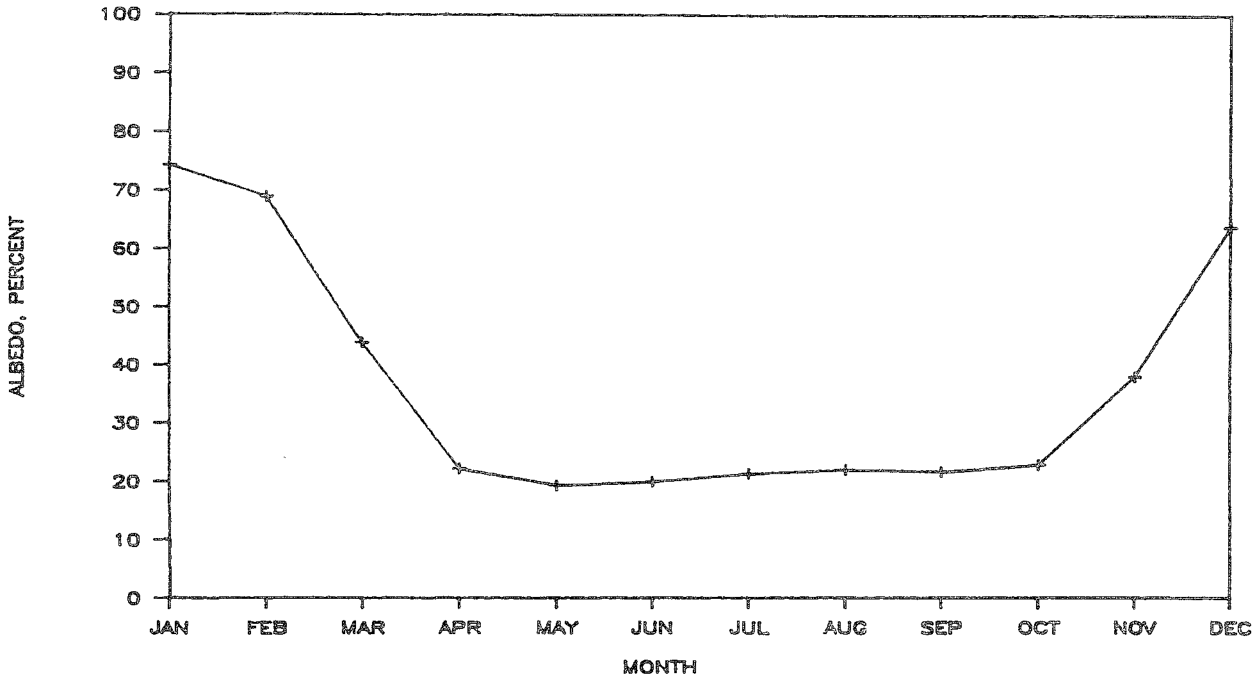

Figure 50. Mean monthly albedo over an agricultural field, St. Paul, 1969-1985. The albedo values are averages of the sod, soybean, pea, and alfalfa covered surfaces.

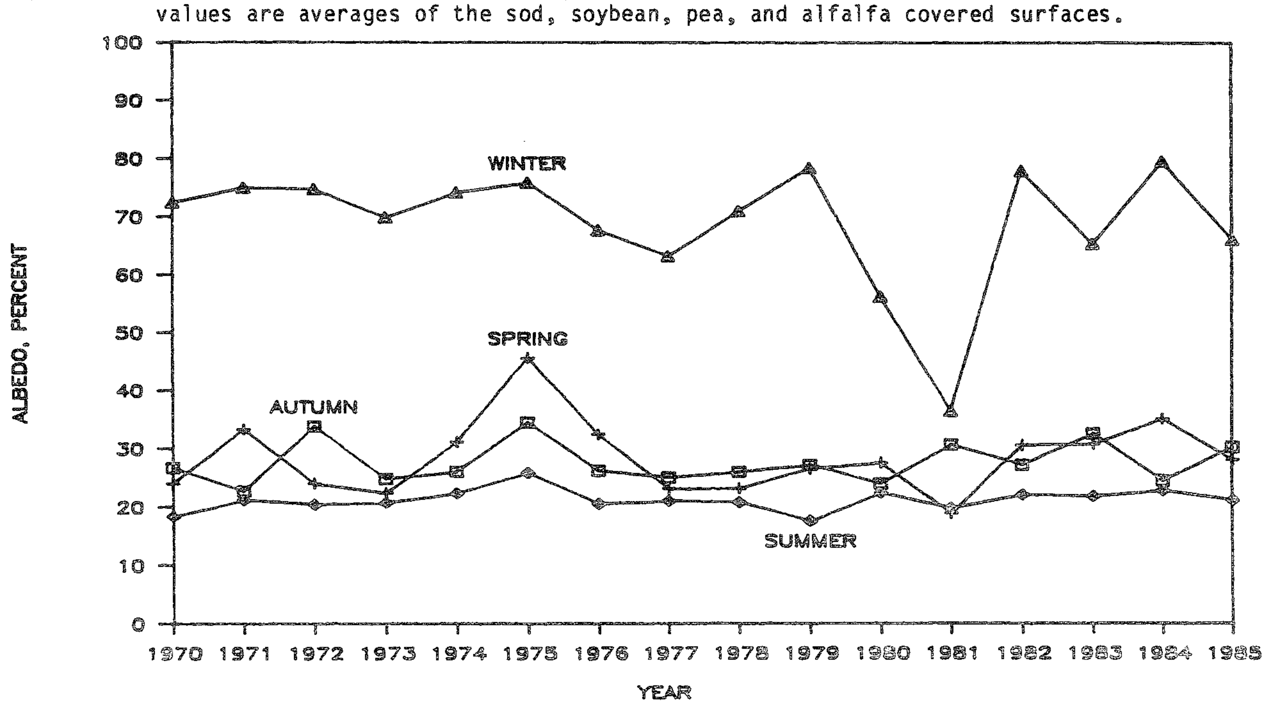

Figure 51. Mean seasonal albedos, St. Paul, 1970-1985. Spring is March-May, summer is June-August, autumn is September-November, and winter is December-February. The winter albedo is plotted for the January-February year.

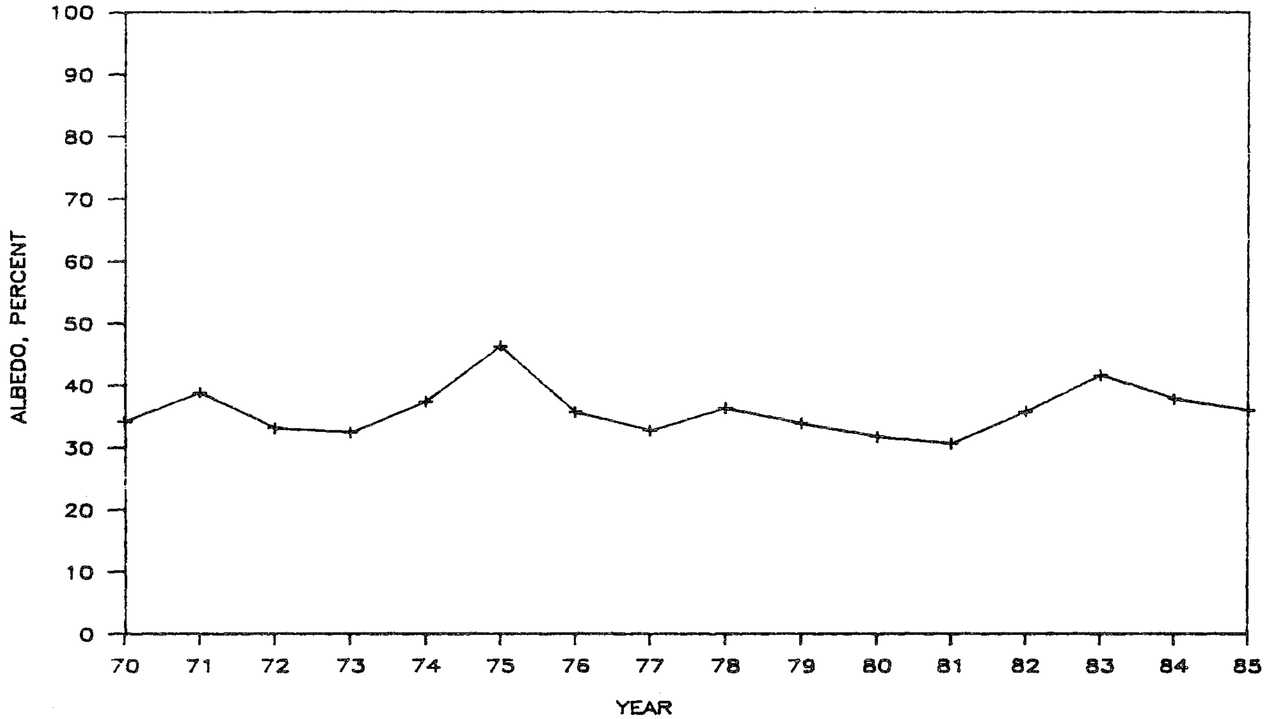

Figure 52. Mean annual albedo, St. Paul, 1970-1985.

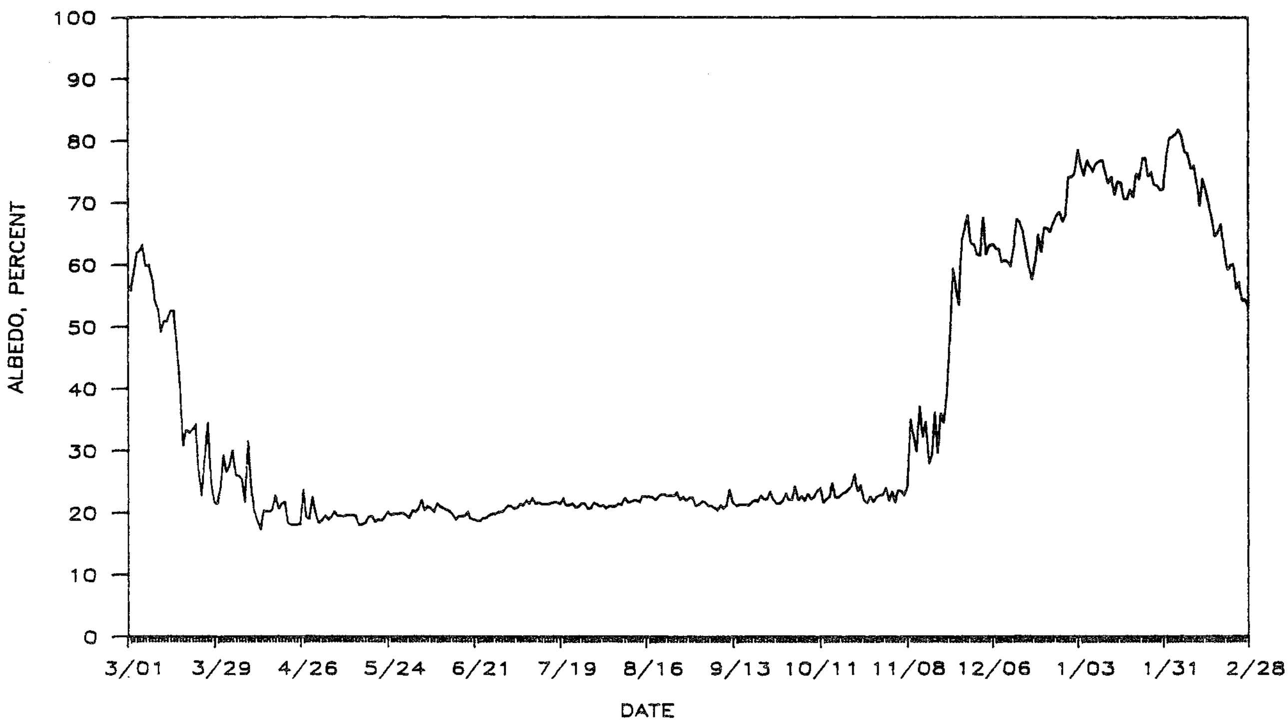

Figure 53. Mean daily albedo over an agricultural field, St. Paul, 1969-1985. The albedo values are averages of the sod, soybean, pea, and alfalfa covered surfaces.

A very common early to mid-April condition is one with a moist or even a wet surface (i.e., one with standing water) that lasts until the soil has completely thawed. For the period 1963-1986 at St. Paul, the mean date when the soil has reached this state is April 8, varying from March 10 to May 6 (Wall, 1987). Because the albedo of still water is only about five percent, its presence greatly reduces the albedo of a surface. From experience it can be concluded that the presence of a wet or moist surface in April is sufficiently frequent to essentially negate the effects of occasional snow cover. March, therefore, becomes the transitional month, in terms of albedo values, between winter and the growing season. November is the other transitional month. The mean first and last dates of a 1-inch (2.5 cm) snow cover are November 22 and March 26, respectively (Kuehnast et al., 1982). The median soil freezing date is November 17 and the complete thaw date is April 7 at St. Paul (Wall, 1987).

The last column in Table 13, headed Normalized to April, is introduced for comparison with a similar study in Wisconsin (Kung et al., 1964). It shows, for example, that the mean January albedo was 3.36 times greater than the April albedo and that the May-September albedos were equal to or less than that of April.

The average daily albedo for the 1969-1985 period, with no distinction made between the crops, is shown in Figure 53. This should be compared to Figure 50 which illustrates the average monthly albedos. Of interest is the abrupt albedo increase in the last third of November as a result of early snowfalls. This is in contrast to the more gradual decrease in albedo that begins in late January and continues to early April. The growing season is remarkably constant at about 22 percent until mid-August. At that time a marked irregularity and a very gradual increase in the albedo occurs which can be attributed to vegetation differences (maturity and leaf fall of the soybeans with increased soil exposure, for example) and drier soil conditions.

The average annual albedo at St. Paul for the 1969-1985 period is 36.5 percent. This agrees with the 35-37 percent albedo shown for Minnesota for a comparable period of time by Vonder-Haar (1974). A value of 33 percent was obtained by Kung et al. (1964) for a Wisconsin station at approximately the same latitude as St. Paul and representing "productive farm land." That value represents a mean of nine flights along selected flight paths over Wisconsin. Their growing season albedo values are similar to those of St. Paul when compensation is made for their beam albedo method and our hemispheric albedo measurement. Their four winter flights averaged 69 percent when converted to hemispheric albedos.

The actual amount of radiation reflected from a surface provides quite a different picture from that of the albedo, as shown in Figure 54. Two things changing at the same time help to explain this difference. Reflectivity of the surface is changing along with the amount of radiation subject to reflection. During February and early March, reflected radiation is at a maximum in response to snow cover and the rapid increase in incoming solar radiation. The sharp drop in reflected radiation in mid-March is due to the change in surface albedo because of the loss of snow cover. The great irregularity in reflected radiation in April, as great as the changes in February, is due to occasional occurrences of snow cover and relatively high radiation values. During May through early July reflected radiation shows a slow but general increase which is associated with the vegetative cover increase. From mid-July until November, a fairly regular decrease is evident. This results from the combination of rapidly decreasing incoming solar radiation together with the less reflective surfaces typical of latter stages of the growing season. This is soon followed by a sharp increase in reflected radiation due to the presence of a snow cover.

The standard deviations and coefficients of variation of seasonal albedo values, Table 13, make it very evident how influential snow cover is in terms of the albedo variation experienced. These results are very similar to those obtained by Kung et al. (1964) from airplane flights across Wisconsin. Weekly reflected radiation and albedo values are in Table 14.

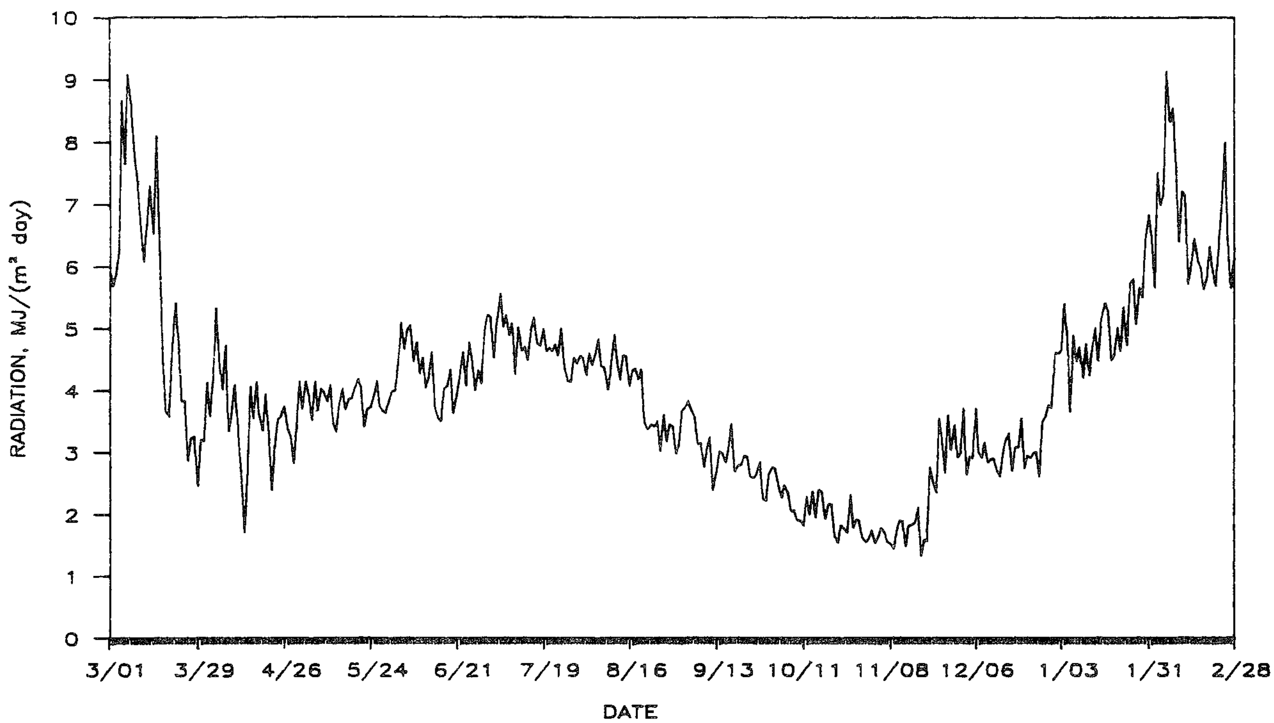

Figure 54. Mean daily reflected solar radiation, St. Paul, 1969-1985.

Table 14. Mean daily reflected radiation, MJ/(m^2 day) and albedo, percent, for sod, soybean, and alfalfa surfaces in each week. *

	SOD			SOYBEAN			ALFALFA		
FIRST DATE	RAD	ALBEDO	N	RAD	ALBEDO	N	RAD	ALBEDO	N
3/01	6.50	60.0	56	10.02	79.0	28	5.11	41.0	28
08	6.70	53.0	56	9.70	66.0	28	5.78	44.0	28
15	5.93	43.0	56	4.32	31.0	28	5.07	51.0	28
22	4.19	33.0	56	2.56	25.0	28	4.60	27.0	28
29	5.06	33.0	56	1.85	13.0	28	2.96	24.0	28
4/05	4.88	28.0	53	3.40	23.0	31	2.83	22.0	28
12	2.93	21.0	49	1.99	13.0	35	5.17	28.0	28
19	3.39	22.0	49	2.45	15.0	35	4.31	21.0	28
26	3.62	24.0	49	2.67	14.0	33	4.21	21.0	30
5/03	4.83	23.0	44	2.90	14.0	33	3.74	20.0	35
10	4.26	24.0	40	2.64	12.0	37	4.34	21.0	35
17	5.00	24.0	35	2.25	12.0	42	4.72	23.0	35
24	4.50	24.0	35	2.79	14.0	42	4.34	23.0	35
31	5.21	23.0	35	3.72	16.0	42	5.06	23.0	35
6/07	5.01	23.0	35	3.65	17.0	42	4.75	23.0	35
14	4.52	23.0	35	2.82	15.0	42	4.40	22.0	35
21	5.22	23.0	35	3.59	16.0	42	4.27	20.0	35
28	5.48	22.0	35	3.97	18.0	42	5.06	22.0	35
7/05	5.29	22.0	35	4.26	20.0	42	5.65	24.0	35
12	5.01	22.0	35	4.81	21.0	42	4.52	21.0	35
19	4.94	21.0	35	4.98	22.0	42	4.31	21.0	35
26	4.65	21.0	35	4.32	23.0	42	4.18	20.0	35
8/02	4.59	21.0	35	4.52	21.0	42	4.37	21.0	35
09	4.25	21.0	36	4.61	22.0	41	4.42	23.0	35
16	3.73	22.0	42	4.15	23.0	35	4.22	23.0	35
23	3.49	23.0	42	3.38	23.0	35	3.25	22.0	35
30	3.60	23.0	42	3.54	22.0	35	3.32	20.0	35
9/06	3.39	24.0	43	2.67	20.0	35	2.99	19.0	34
13	3.55	24.0	49	2.43	17.0	35	2.60	23.0	28
20	3.17	26.0	49	1.98	17.0	35	3.02	24.0	28
27	3.08	25.0	53	1.77	16.0	31	2.50	25.0	28
10/04	2.34	24.0	56	1.41	16.0	28	2.50	25.0	28
11	2.51	26.0	56	1.61	14.0	28	2.03	27.0	28
18	2.29	28.0	55	1.04	15.0	28	1.84	27.0	28
25	2.02	25.0	49	1.03	15.0	28	2.28	25.0	28
11/01	1.95	26.0	49	1.07	16.0	28	1.73	25.0	28
08	1.57	30.0	49	1.75	32.0	28	1.80	36.0	28
15	1.88	34.0	50	1.67	31.0	28	2.10	35.0	28
22	2.97	56.0	56	3.83	78.0	28	2.20	52.0	28
29	2.70	62.0	56	4.29	79.0	28	2.62	53.0	28
12/06	3.18	64.0	53	3.57	68.0	28	2.31	52.0	28
13	3.13	72.0	49	2.65	61.0	28	2.93	54.0	28
20	3.36	74.0	49	2.38	57.0	28	3.14	59.0	28
27	4.00	76.0	51	3.34	65.0	28	3.78	69.0	28
1/03	5.20	83.0	49	4.73	76.0	28	3.62	69.0	28
10	4.94	82.0	49	4.03	66.0	28	4.72	72.0	28
17	5.45	80.0	54	4.27	63.0	28	4.70	67.0	28
24	5.48	76.0	56	6.33	80.0	28	4.94	69.0	28
31	6.76	79.0	56	7.60	79.0	28	7.31	83.0	28
2/07	7.07	71.0	56	8.10	77.0	28	6.81	82.0	28
14	5.98	66.0	56	7.83	77.0	28	4.42	62.0	28
21	5.89	53.0	56	8.01	71.0	28	5.89	54.0	28

* N is the number of daily observations in each climatological week.

Snow covered Surfaces

It has been observed that the major factor with respect to the amount of reflected radiation is the presence or absence of snow (Bauer and Dutton, 1962; Kung et al., 1964). All other surface features have minor effects on reflected radiation. It is only in the absence of snow that features such as the kind and density of vegetation, soil color and moisture, and tillage treatments assume importance. This is amply illustrated in Figures 50 and 51. During snow-free periods the albedo is less than 30 percent with 20-25 percent being typical. In the presence of snow the albedo is ordinarily at least 50 percent, and averages as high as 80 percent during much of January when snow cover is most often present.

It can probably be accepted that in Minnesota an albedo or reflection coefficient that is 50 percent or less, but still higher than about 25-30 percent, is the result of very dirty and aged or melting snow. The Corps of Engineers (1956) found that for a deep, non-melting, mountain snow pack during the accumulation season, but in the absence of fresh snow, the albedo gradually decreased to a value of about 60 percent. In that environment the reduction to 60 percent required a period of about 15-20 days. In the same length of time for a deep but ripe and granular snowpack in the melt season, the albedo approached 40 percent (Corps of Engineers, 1956; Dirmhirn and Eaton, 1975). Another way in which values less than 50 percent occur is when snow is so shallow, probably 4 in (10 cm) or less according to the results of Wall (1987), that the soil or vegetation background under the snow is influencing the amount reflected. Kung et al. (1964) found that about 5 in (13 cm) of snow were required to negate underlying effects.

Winter snow cover at St. Paul is largely confined to December-February, with November and March ordinarily representing transitional months, as noted earlier. The snow-free season is, with few exceptions, April-October. This is very clear in Figures 50 and 53. When viewed on a daily basis a more precise timing of the albedo shift is obtained, as shown in Figure 53.

Examples of three kinds of winter albedos are depicted in Figures 55-57. A winter in which there were shallow snowfalls combined with a non-persistent snow cover is that of 1980-1981, Figure 55. This was virtually an "open" winter of very little snow. Only in the first half of February was the snow sufficiently deep to produce an albedo of 60 percent or more. The occasional "blips" of an albedo increase of 40-60 percentage units indicate a very shallow snow of only brief duration. The albedo for the December-February period averaged only about 36 percent, indicating that the underlying soil or vegetated surface was affecting the albedo considerably.

The winter of 1981-1982, Figure 56, was one of an early, continuous, and deep snow cover. As a result, the effect of the underlying soil and vegetation surface has been completely obscured and the albedo averaged 78 percent for December-February. Fresh snowfalls brought the individual daily albedos up to considerably more than 80 percent. Due to the deep and continuous snow cover until the second week of March, the soil froze only shallowly. It was very easy to pick out the times of the beginning and end of "winter" by simply observing albedo values. The late March low spring albedo of about 15 percent was due to a snow-free alfalfa cover of insufficient density to completely obscure the moist soil.

A third kind of winter, 1984-1985, is shown in Figure 57. This winter was one of frequent snowfalls but an intermittent snow cover except in January to mid-February. Its December-February mean albedo was 66 percent. The fresh snow albedo ranged between 75-90 percent. However, within a few days it dipped to only 20-25 percent, because the snow cover was shallow and intermittent or had disappeared entirely, exposing the sod surface.

In addition to the major difference in albedo that exists between snow and no-snow conditions, an important phenomenon, already discussed briefly, is illustrated in Figures 55-57. This is the aging (also termed metamorphosis) of the snow following each snowfall. The rate at which it occurs is not uniform. It depends on changes in the structure of snow crystals, which are a function of snow temperature and wind action. Another feature decreasing the albedo of snow is the increasing dirtiness of snow following its deposition. The "dirt" consists largely of smoke particles, usually local in origin, and sometimes soil particles or "dust", usually of local origin but occasionally from quite distant sources. This process of

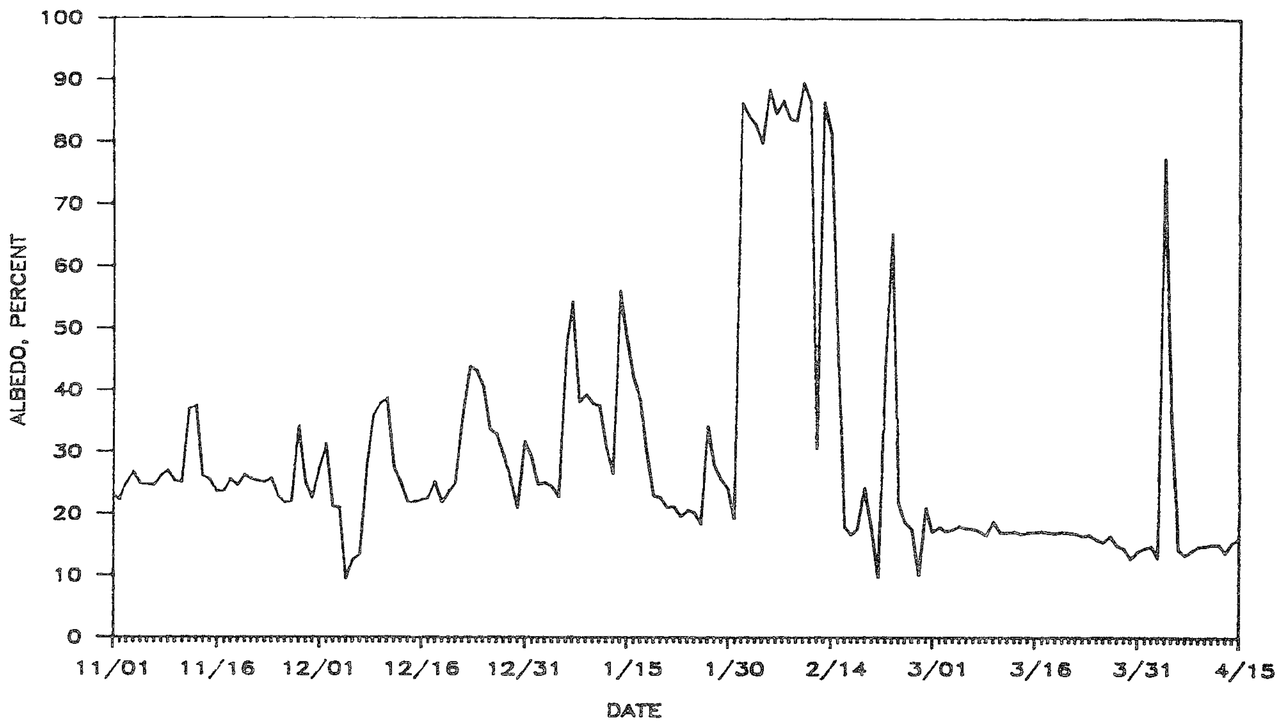

Figure 55. Daily albedos for the snowfall season of 1980-1981, a season of light snowfalls and non-persistent snow cover at St. Paul.

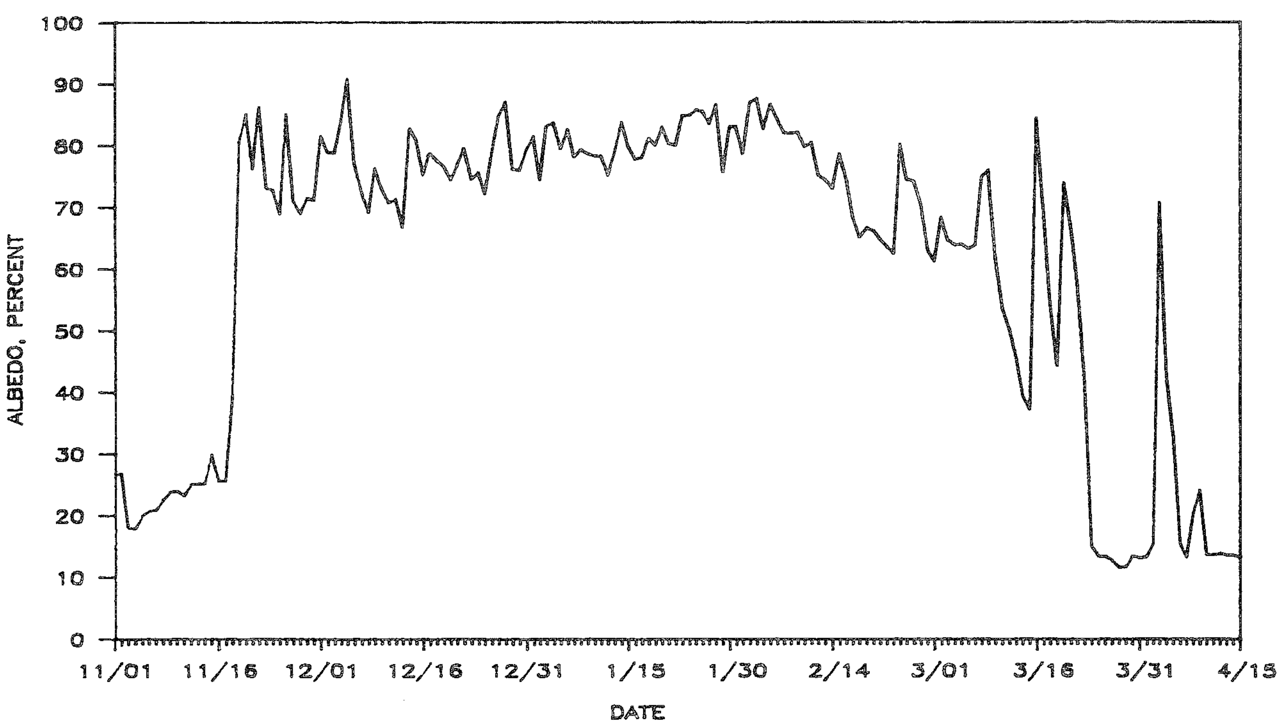

Figure 56. Daily albedos for the snowfall season of 1981-1982, a season of an early, deep, and persistent snow cover at St. Paul.

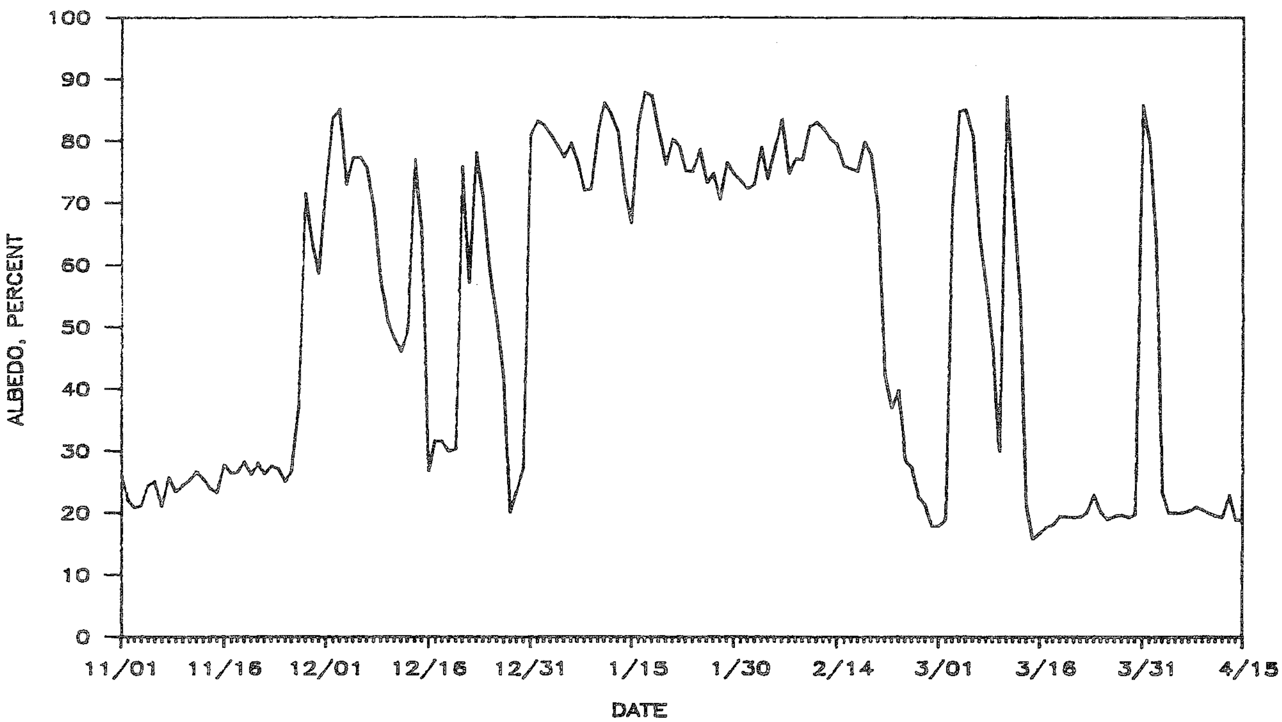

Figure 57. Daily albedos for the snowfall season of 1984-1985, a season of frequent snowfalls and non-persistent snow cover except in January and February.

Figure 58. Mean daily albedos for the November-April period, St. Paul, 1969-1985.

change is shown in Figures 55-57 by the abrupt increase in the albedo, indicating a fresh snow cover, followed by the (usually) more gradual decreases in albedo as a result of the metamorphosis and perhaps the accumulation of foreign matter on the snow surface.

While the differing snow conditions of three individual years are illustrated in Figures 55-57, daily average conditions for the entire 1969-1985 period are depicted in Figure 58.

Some individual days illustrate even better the marked contrast between the snow and no-snow conditions and the change that takes place as the snow melts. The change in reflected radiation that occurred over a five day period from March 14 to March 18, 1970 is illustrated in Figure 59. Although incoming solar radiation was nearly equal on all five days, reflected radiation and albedo decreased markedly as the cover, which began as a 3-4 in (7.6-10 cm) blanket of aged and granular snow, melted and left a very moist surface covered with a mixture of ice and water. Details of the five days are listed in Table 15. The 13.4 percent albedo on March 18 is indicative of a moist soil surface.

A remarkable example of the albedo difference that can be observed in just one day was exhibited on March 30, 1970, Figure 60. That day began with a fresh but shallow snow cover of about 1 in (2.5 cm), and the resulting albedo at 0945 hours was 61.7 percent. By 1130 hours the snow had completely disappeared and reflected radiation had decreased markedly, to 13.7 percent. The resulting albedo was typical of a moist sod surface. The mean albedo for the day was 30.1 percent.

Table 15. Physical details of the environment at the microclimate station, March 14-18, 1970.

	Date				
	3/14	3/15	3/16	3/17	3/18
Incoming Solar, MJ/(m^2 day)	18.75	18.79	17.75	18.12	18.42
Reflected Solar, MJ/(m^2 day)	12.51	11.76	8.25	4.31	2.47
Albedo, percent	66.7	62.6	46.5	23.8	13.4
Surface Conditions	3-4 in snow	2-3 in snow	0-1 in snow	sod & ice	sod, ice, & water
Air Temperature, Maximum, °F	29°	29°	36°	38°	41°

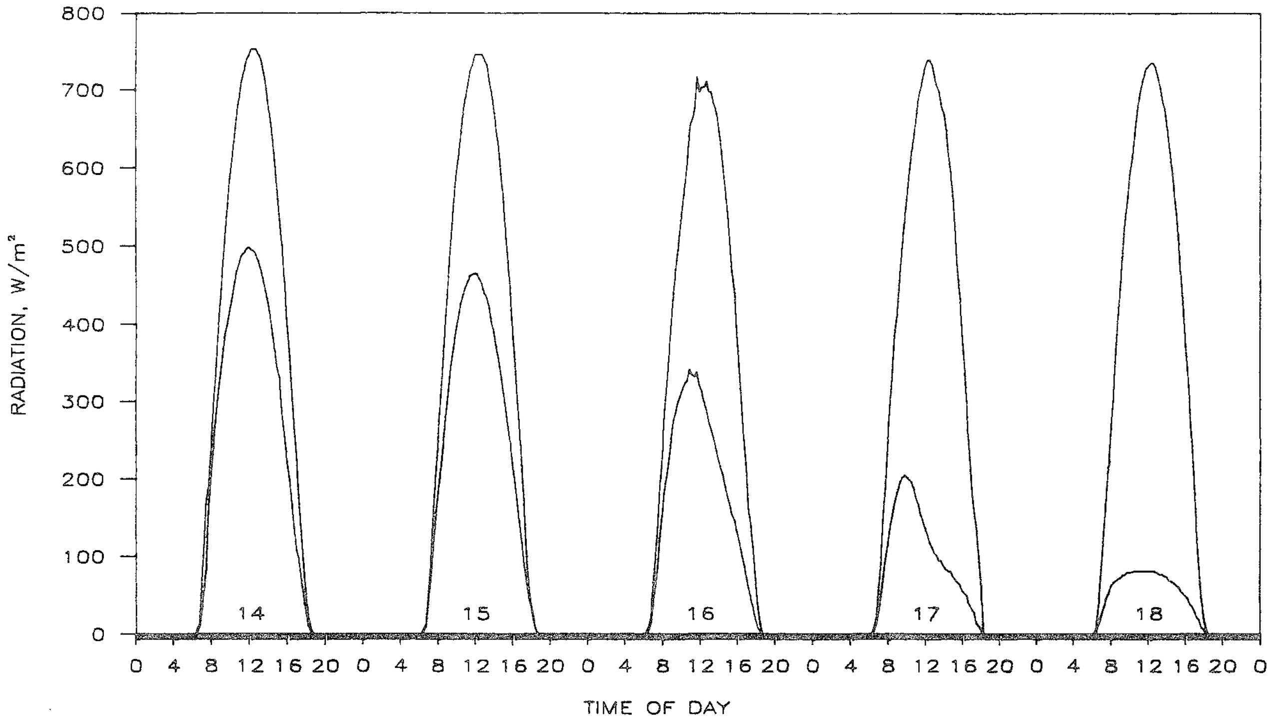

Figure 59. The total incoming and reflected solar radiation measured over a sod surface on March 14-18, 1970.

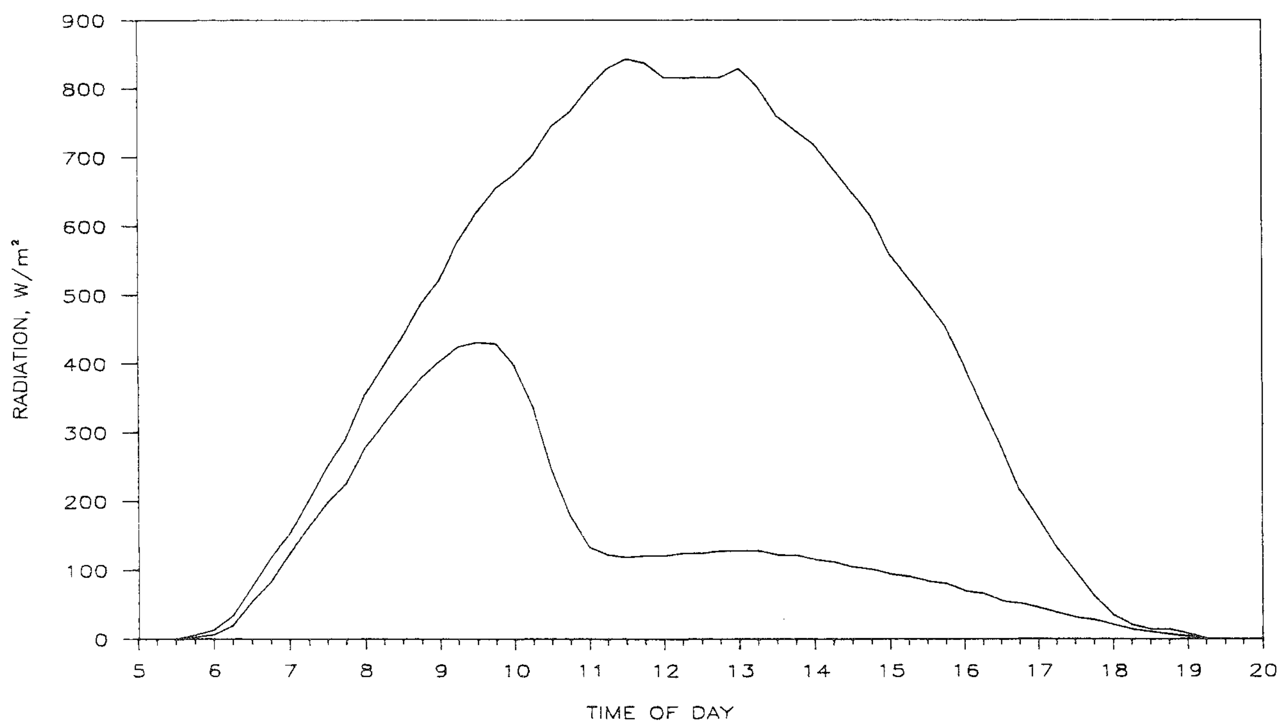

Figure 60. The total incoming and reflected solar radiation measured over a sod surface on March 30, 1970.

Snow-Free Surfaces

Although an experimental plot bare of vegetation was not established exclusively for albedo measurements, there were numerous occasions when the soil was partially or completely bare of vegetation. This generally occurred in the spring from the time of the disappearance of snow cover until the crop emerged, in the late summer as the annual crop matured, and in the autumn after harvest. Bare soil also occurred on those few winter occasions when the surface was devoid of both snow and vegetation.

In general, freshly roto-tilled and friable topsoil exhibited an albedo of 11-12 percent, which reached a maximum of 16-18 percent after an extended drying period. An absolute maximum of 20 percent was reached when the exposed surface was smooth and air dry. When the soil moisture content increased, with the topsoil going from moist to wet, the albedo dropped to about 10 percent and 8 percent, respectively. With standing water on the bare soil, resulting from snow melt or a heavy rain, albedo dropped to 8 percent or less. The absolute minimum recorded was 2.4 percent.

Of the 5778 total albedo days in the record there were 33 which had albedos equaling 8 percent or less. On all 33 days the soil was either extremely wet or had water standing on it. Since free water has an albedo of about 5 percent as long as the solar altitude exceeds about 40°, the low albedos resulting from a combination of water and soil should not be surprising.

The vegetation surfaces for which reflection has been measured include sod, peas, soybeans, and alfalfa. Measurement periods for each type of plant cover are in Table 16.

Table 16. Chronology of the reflection measurements made at St. Paul.

Cover	Period
Sod	Nov. 21, 1969 - May 4, 1970
Soybeans	May 5, 1970 - Sept. 29, 1970
Sod	Sept. 30, 1970 - May 14, 1971
Soybeans	May 15, 1971 - May 19, 1972
Peas	May 20, 1972 - August 14, 1972
Sod	Aug. 15, 1972 - April 8, 1977
Soybeans	April 9, 1977 - April 30, 1980
Alfalfa	May 1, 1980 - Sept. 11, 1984
Sod	Sept. 12, 1984 - Dec. 31, 1985

Albedo often provides a "signature" identifying the surface being measured. As a result, the vegetation and treatment or agricultural practice can be identified by knowing the albedo over a growing season. Figures 61-63 demonstrate this. The 1985 season, Figure 61, is a good example of the characteristic albedo of a well watered sod surface. With few exceptions, the albedo remained at about 22 percent. Probably due to greater trapping of solar radiation by the erectophile grass blades, the reflection is lower than the approximately 25 percent albedo of many agricultural crops (Monteith, 1959; Rosenberg _et al._, 1983).

Features typical of an alfalfa crop are apparent in Figure 62. This is the 1982 season, which was the third year for the alfalfa. The first feature to note is the decrease from the general albedo value of about 25 percent to about 18 percent when the alfalfa was cut. It is obvious that three cuttings were obtained, June 10, July 12, and August 18. The recovery period following each cutting varied due to weather conditions, particularly the frequency and amount of precipitation.

There are two things to note in Figure 62 which are not related to the vegetative cover. One is an early April snow of very brief duration. This is readily apparent in the daily albedo values. And second, following the disappearance of snow but before the alfalfa began growing, the albedo averaged about 12 percent. This indicates exposed moist soil. There was probably meltwater standing on the surface.

An example of two surface conditions is the 1970 season, Figure 63. Prior to May 5, the inverted pyranometer was over the sod plot. A dry late March and early April is shown by lower than expected sod albedos in early April. Two light snowfalls on April 13 and April 21 give a short term jump in albedo. The moisture from the snow and from a rain on April 19-20 caused the grass to green up and the albedo increased. More rain on April 28, 29 and May 1 saturated the soil and reduced albedos for a few days. On May 4 the soybean plot was cultivated and the soybeans were planted the following day.

The instrument was moved to the soybean plot on May 5. The albedo trace shows several sharp drops in albedo due to rain on May 9, 14, 22-24, and 27-31 with subsequent slow increases in albedo as the soil dried. By about June 10 the soybean cover was increasing and by mid-July there was complete cover presented to the inverted pyranometer. From then until mid-August the albedo averaged 23-25 percent. With maturity in late August, which included both a change in the leaf color and an increasing amount of exposed soil due to leaf fall, the albedo decreased to 12-15 percent. On September 30, the inverted pyranometer was moved back to the sod plot.

Assuming adequate soil moisture and typical growth of the soybeans, the change in albedo is quite regular as the plant cover changes. As a result, the amount of cover can often be predicted from the albedo value as shown by Blad and Baker (1972).

The important points that are to be observed in Figures 61-63 are summarized in Table 17. The peas, for which there was one crop season, are very similar to the soybeans. As a legume and an annual row crop this is to be expected. The mean growing season albedo of the four crop covers is shown in Figure 64.

Table 17. Albedo features typical of four different vegetative surfaces at St. Paul.

Surface	Typical Albedo Features
Sod	1. A remarkably uniform seasonal albedo of about 22 percent occurs in years of adequate soil moisture. 2. Variations from the 22±2 percent range are due to moisture stress.
Soybeans	1. Following cultivation and seeding, the albedo is that of the soil. 2. The spring variation in albedo before the beans provide complete cover is due to the wetting, following precipitation, and the subsequent drying of the soil. 3. The albedo gradually changes to about 20-25 percent as the soybean leaf area increases and exposed soil area decreases; little variation in albedo occurs once about 75-80 percent cover is reached; plants subject to moisture stress will show a decrease of about 5 percent (assuming a soil of similar characteristics to the Waukegan soil), although this can be exceeded in periods of unusual stress. 4. The albedo shows a relatively rapid decrease once maturity is reached and leaf fall begins; the albedo may remain higher than at the beginning of the season, since fallen leaves prevent complete exposure of the soil and the soil is usually drier.
Peas	1. A very similar series of events to that of soybeans occurs, but in a briefer period.
Alfalfa	1. Except in the planting year, a relatively uniform albedo of about 25 percent occurs from beginning to end of the season. 2. An exception occurs when the alfalfa is cut, at which time the albedo is reduced nearly to the bare soil value. 3. With adequate water the alfalfa shows a recovery period of about 10-14 days following cutting, at which time the new growth results in the return of the albedo to its initial value of about 25 percent.

Note: The albedo of sod appears to be slightly lower than the full cover albedo of either soybeans or alfalfa. The vertical grass blades would be expected to trap more radiation than more horizontally oriented soybean and alfalfa leaves.

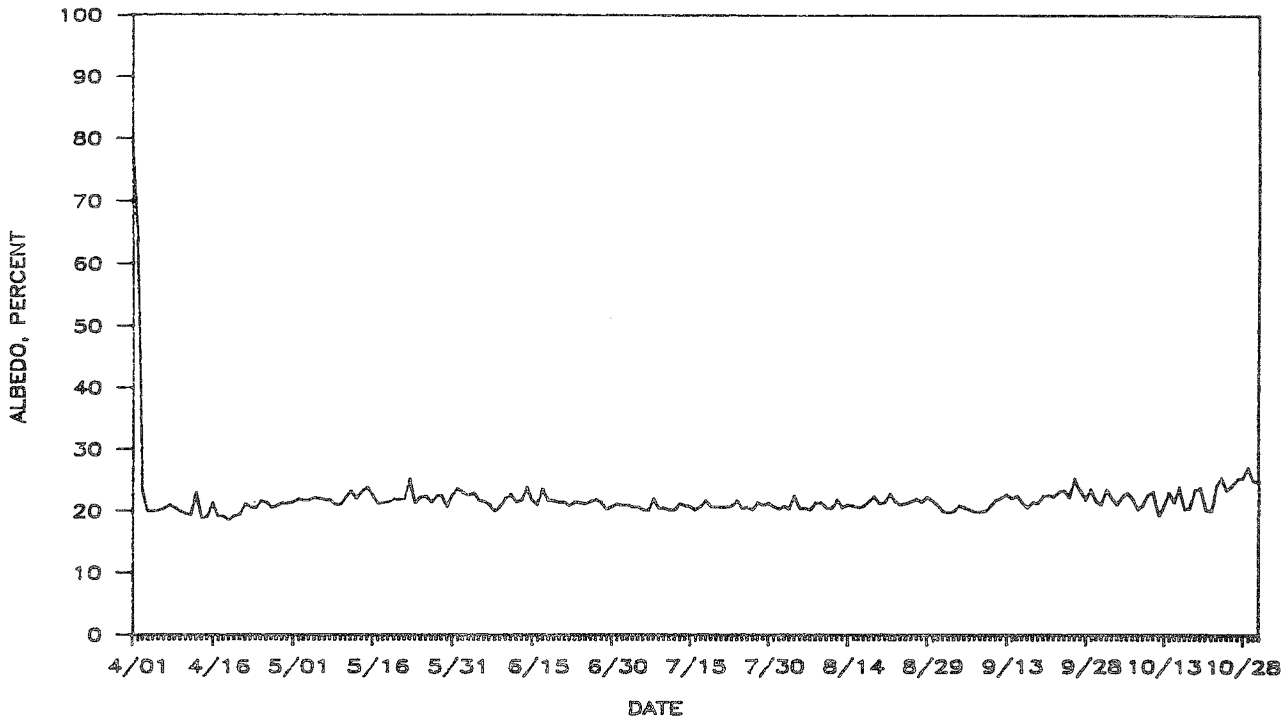

Figure 61. Daily albedos over a well-watered sod surface, St. Paul, April-October, 1985.

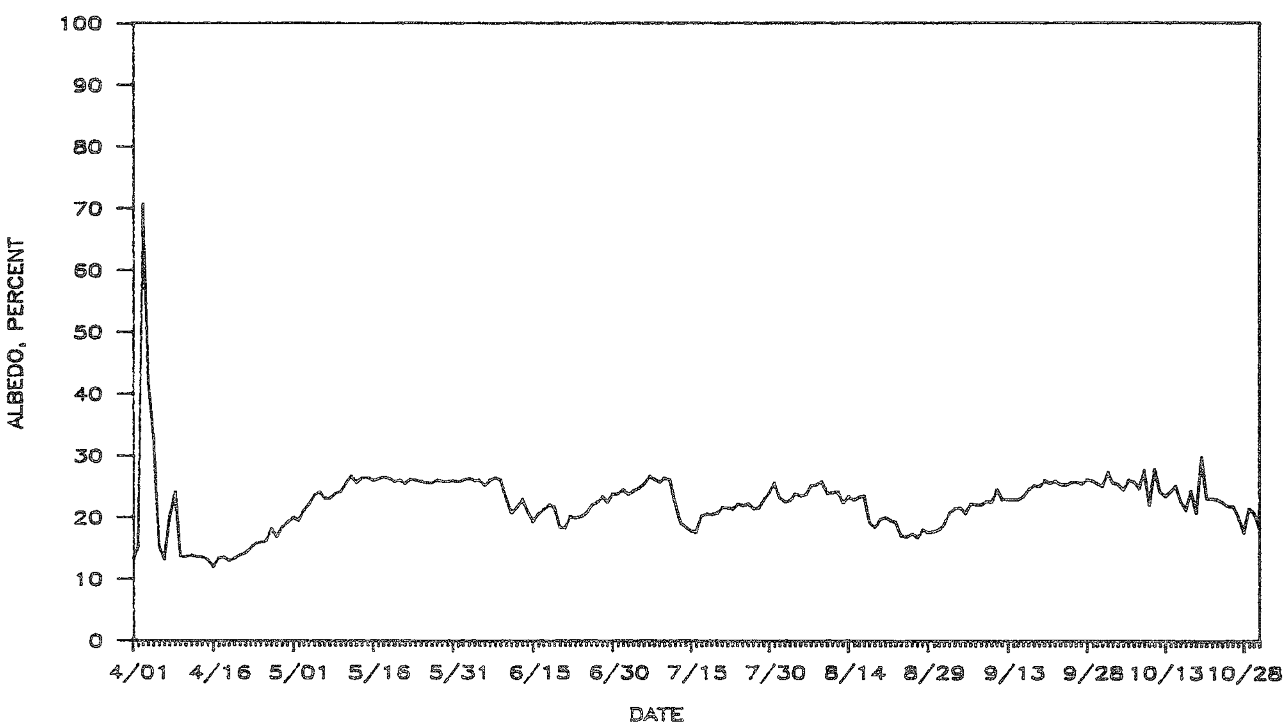

Figure 62. Daily albedos over an alfalfa field, St. Paul, April-October, 1985.

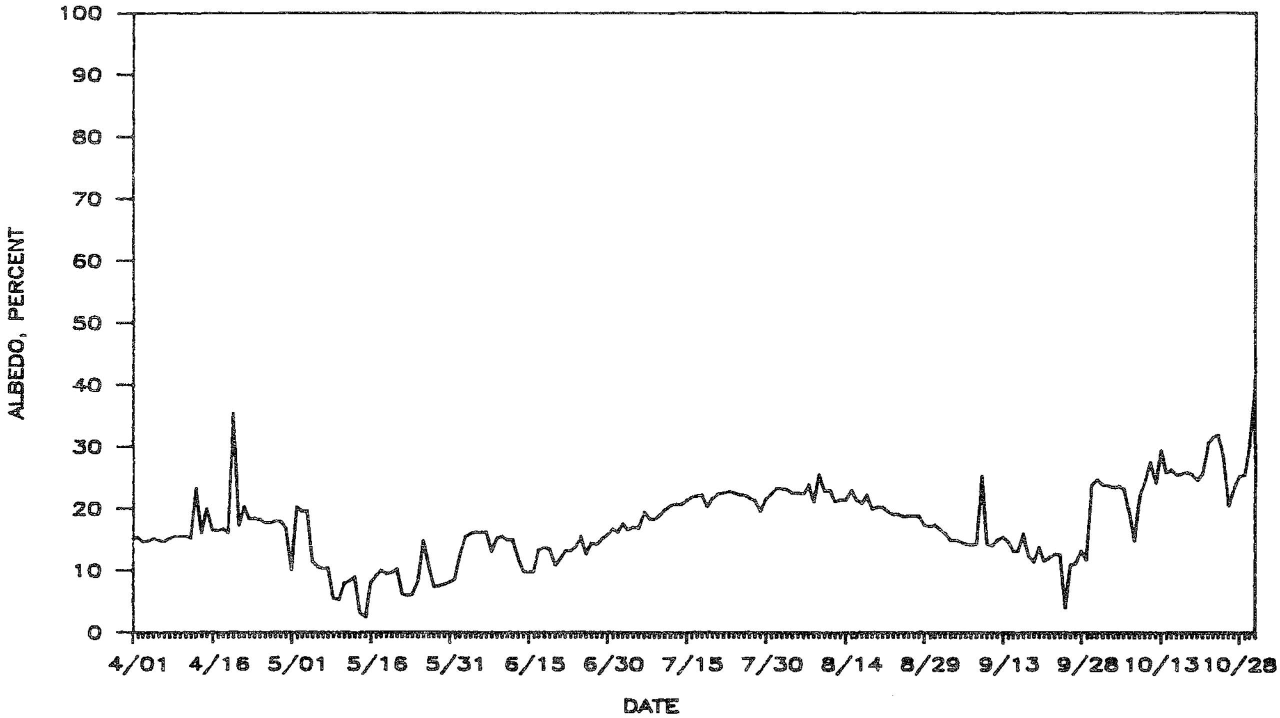

Figure 63. Daily albedos over a soybean field, St. Paul, April-October, 1970.

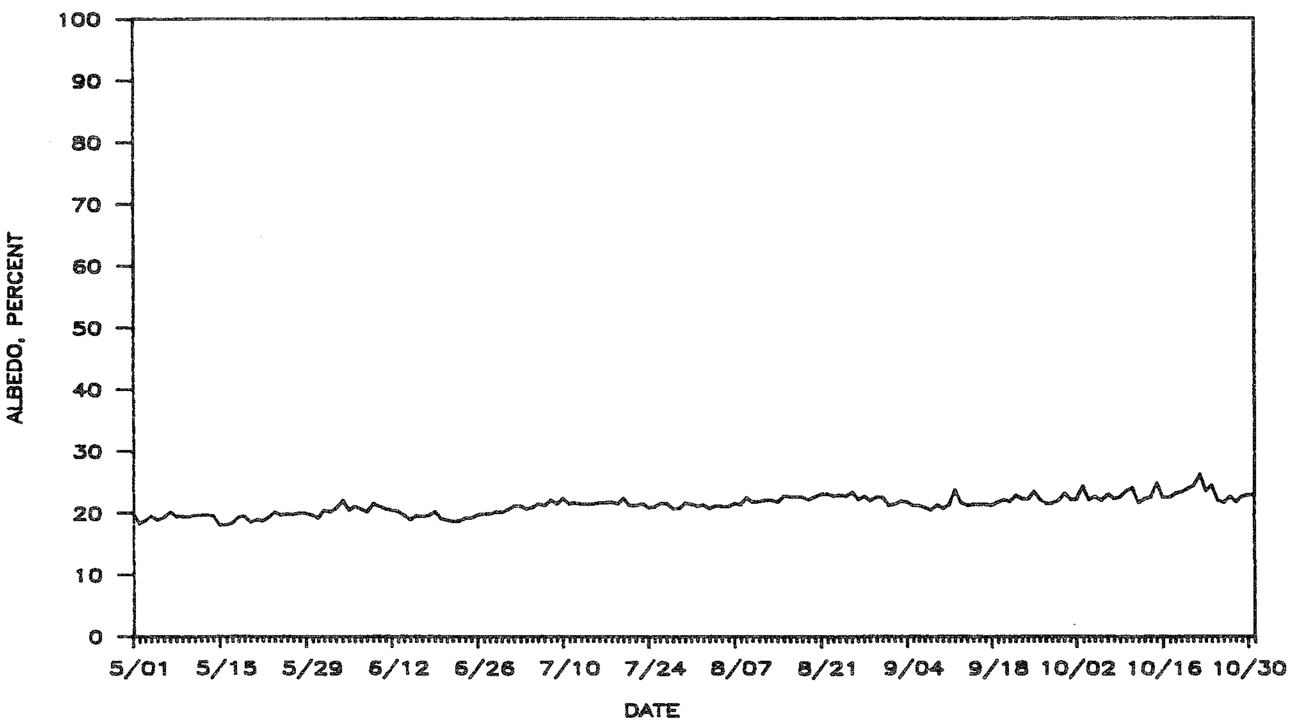

Figure 64. Mean daily albedos of the four vegetative surfaces (sod, alfalfa, peas, and soybeans) May-October, 1969-1985.

NET SOLAR RADIATION

In Figure 65 reflected solar radiation has been subtracted from total solar radiation (top curve), leaving what is termed net solar radiation (bottom curve). This is the solar radiation absorbed at the surface of the earth. The addition of the net longwave radiation to the net solar, resulting in the net total radiation, would not appreciably alter the shape of the trace shown in Figure 65, but it would decrease the daily values shown by about 4 $MJ/(m^2 day)$[95 $cal/(cm^2 day)$] in the winter and 6 $MJ/(m^2 day)$[142 $cal/(cm^2 day)$] in the growing season. Both net total and net solar radiation are used in the following ways: evaporation, heating the air, heating the soil, photosynthesis, and storage at the surface in the crop. The amount used to heat the soil accounts for no more than about 10 percent of the net, and usually less. The amounts used in photosynthesis and storage are even less. The two major items to which net radiation is directed are evaporation, termed evapotranspiration in the case of a vegetated surface, and in heating the air. It is readily apparent, therefore, that net solar and net total radiation are true climatic determinants.

Maximum net solar radiation does not occur at the time of the maximum solar elevation and longest day, June 22. Its occurrence is delayed about one or two weeks due to the cloud cover common in mid- to late June. Minimum net solar radiation is reached in December and January due to the combination of low solar radiation (short days and much cloud cover) and highly reflective snow cover.

The minimum difference between total incoming and net solar radiation, or the reflected solar radiation, is found in early November. Since snow cover at this time is unusual, the reflected radiation is at a minimum due to the generally dry state of the soil surface and the vegetation. This is also shown in Figure 54.

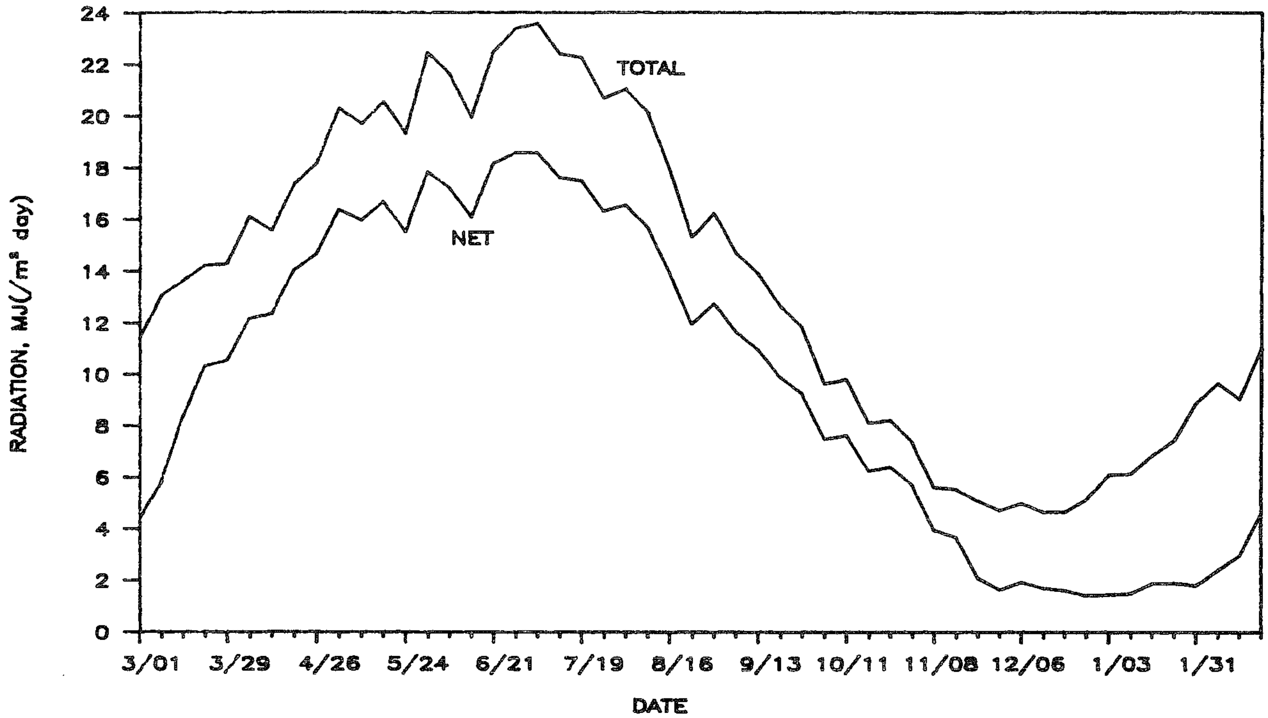

Figure 65. Mean daily total solar and net solar radiation, St. Paul, 1969-1985.

RADIATION DURING ECLIPSES

Four partial eclipses have occurred and been measured at St. Paul since the solar radiation recording began. These were dated March 7, 1970, July 10, 1972, February 26, 1979, and May 30, 1984.

Total incoming solar radiation on a horizontal surface during the eclipse of May 30, 1984, is illustrated in Figure 66. Most of the day, and particularly during the eclipse, the sky was free of clouds. The eclipse began at 0912 CST, a maximum coverage of the sun was reached at 1027 CST, and the eclipse was completed by 1242 CST. The path of the total eclipse was well east of St. Paul as it passed over the cities of New Orleans, Atlanta, and Richmond. As a result, the announced solar radiation reduction at St. Paul was to be 54.7 percent.

Based on the minute by minute recording of the pyranometer output, Figure 66, the reduction in solar radiation was 54.0 percent. That is, at 1027 CST a minimum of 404.6 W/m^2 [0.58 cal/(cm^2 min)] was recorded compared to 865.0 W/m^2 [1.24 cal/(cm^2 min)] received at 1027 CST on the following day, May 31, plus a 13.9 W/m^2 [0.02 cal/(cm^2 min)] correction for the difference in turbidity of the atmosphere. The very slight difference between the two percentages was possibly because a part of the pyranometer measurement includes diffuse radiation along with the direct beam.

Pyrheliometer output during the partial eclipse is illustrated in Figure 67. Since this instrument is not affected by diffuse radiation, its response to the partial eclipse is greater and more immediate than the pyranometer's, depicted in Figure 66. The calculated reduction from the expected value of 899.9 W/m^2 [1.29 cal/(cm^2 min)] to a minimum of 397.6 W/m^2 [0.57 cal/(cm^2 min)] at 1027 CST is 55.8 percent.

The trace measured with the 55° south-facing pyranometer is shown in Figure 68. Based on the expected clear-day value and the measured minimum value at 1027 CST, 788.3 W/m^2 [1.13 cal/(cm^2 min)] and 369.7 W/m^2 [0.53 cal/(cm^2 min)] respectively, the reduction in solar radiation amounted to 53.1 percent.

The inverted pyranometer measuring reflected radiation showed a reduction from 181.4 W/m^2 [0.26 cal/(cm^2 min)], the value just before and immediately after the partial eclipse, to a minimum of 97.7 W/m^2 [0.14 cal/(cm^2 min)] at 1027 CST. This gives a reduction of 46.2 percent. Why this result is less than the others is not clear.

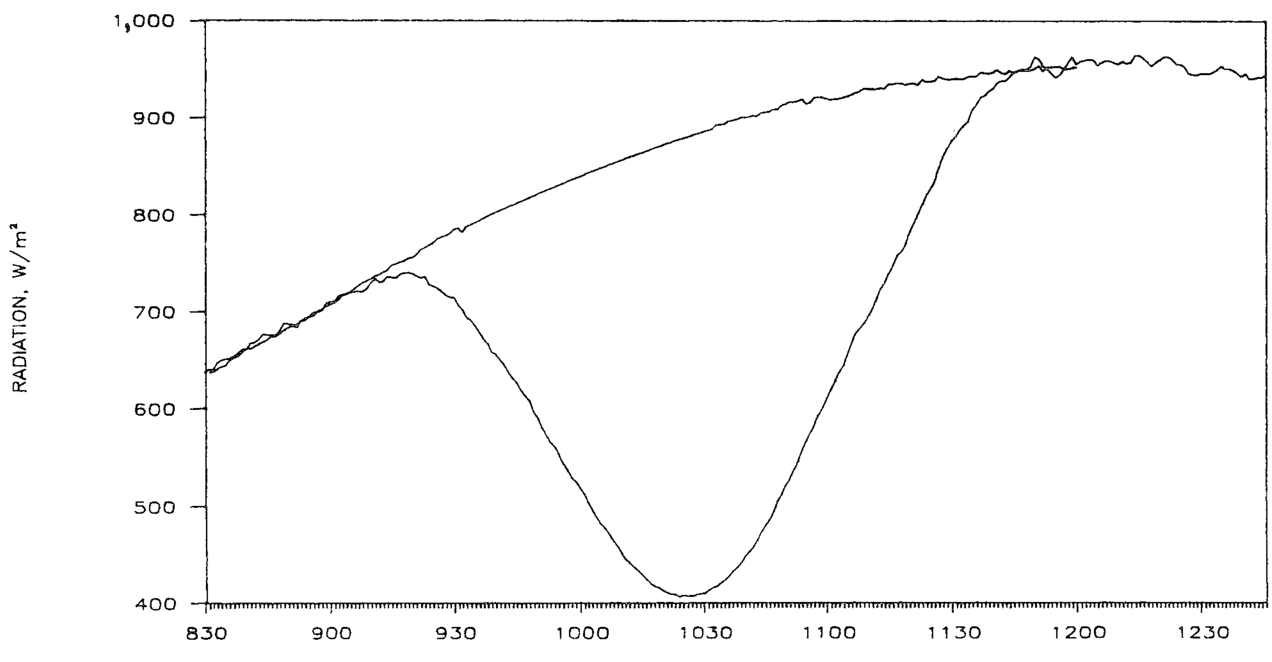

Figure 66. The partial eclipse of May 30, 1984, as measured by the upright pyranometer. The radiation shown during the eclipse period is that of May 31.

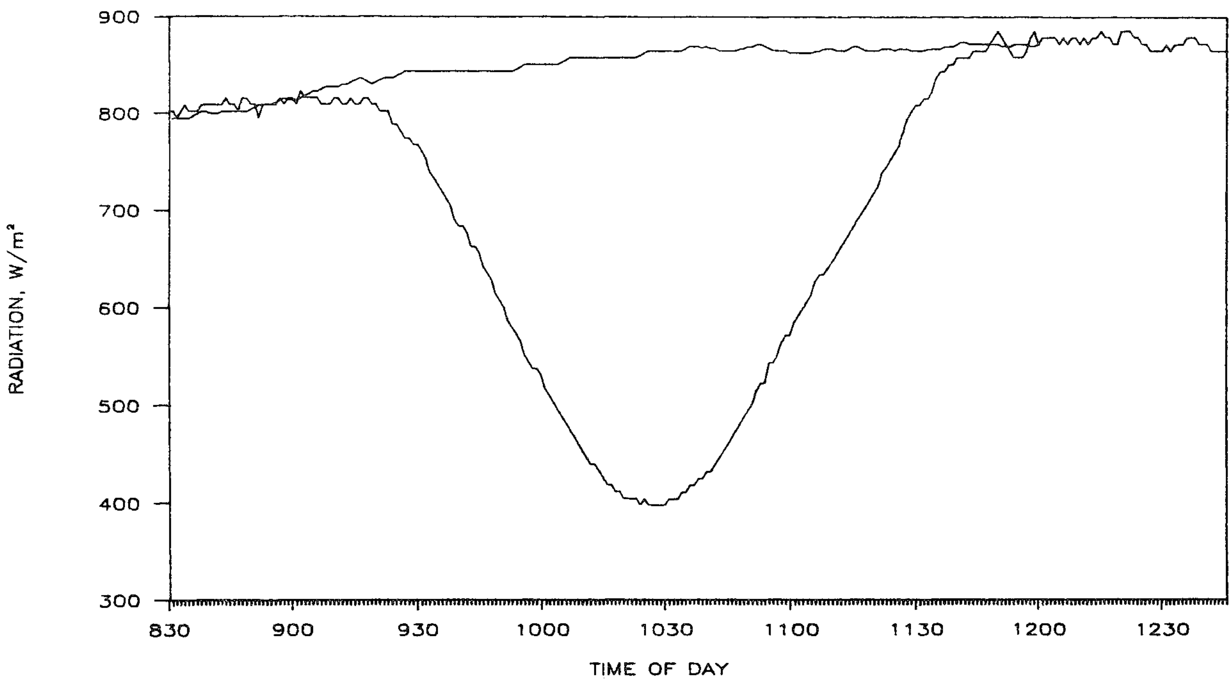

Figure 67. The partial eclipse of May 30, 1984, as measured by the pyrheliometer. The radiation shown during the eclipse period is that of May 31.

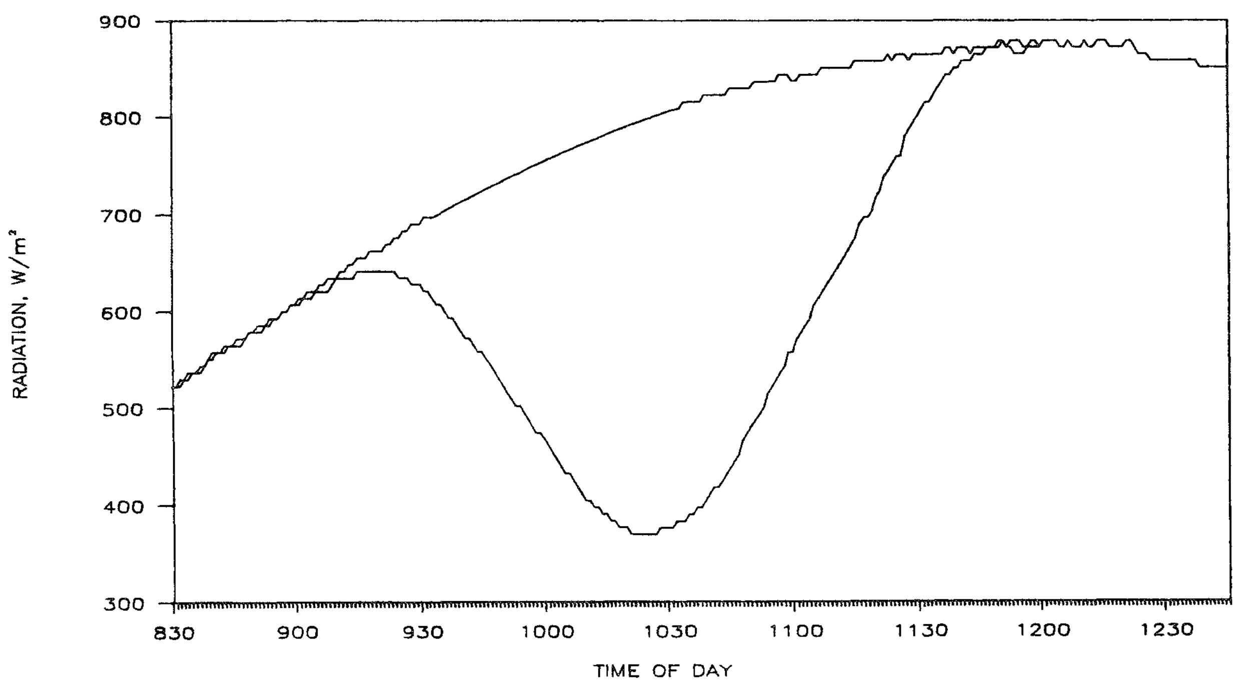

Figure 68. The partial eclipse of May 30, 1984, as measured by the 55° south-facing pyranometer. The radiation shown during the eclipse period is that of May 31.

SUMMARY

This bulletin summarizes solar radiation measurements made at St. Paul during the period 1963-1985. It is intended to augment information presented in earlier bulletins. It includes incoming total solar radiation on horizontal (1963-1985) and non-horizontal (1979-1985) surfaces, outgoing (reflected) total solar radiation (1969-1985), diffuse and direct beam radiation on horizontal surfaces (1977-1985), and normal incidence direct beam radiation (1980-1985). The bulletin brings up to date information such as statistics of radiation, clear-day and mean daily values, and the amount of radiation received at given probability levels. New information is also presented that includes radiation received on other than horizontal surfaces, reflected radiation, albedos of different natural surfaces, and diffuse, normal incidence, and net solar radiation values. An unusual feature that is included is the radiation reception during a partial eclipse. It is believed that the material presented in this bulletin will answer most questions that might be raised relative to solar radiation at this location.

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